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LAPWORTH, C. 1878. The Moffat Series. *Quart. Journ. Geol. Soc.*, xxxiv, 240–343.

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GEOLOGICAL MAGAZINE

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Depth of Burial of South Wales Coals

By H. W. WELLMAN (New Zealand Geological Survey, Greymouth)

ABSTRACT

Metamorphism of the South Wales coals is considered to be due to depth of burial and not to a thrust. Dr. Trotter's data are used to calculate the metamorphic gradients at different places. The differences in these gradients, which are calculated in two different ways, are discussed. The South Wales gradients together with data from New Zealand are used to estimate 18,000 feet as being the total depth to which the 4 per cent anthracite was buried. Maximum depth of burial is considered due to cover unconformable to the coal measures except in the southern part of the coalfield.

INTRODUCTION

IN a recent paper by Dr. F. M. Trotter (1949) an attempt was made to explain how and why coals of different rank are distributed the way they are in South Wales. His explanation is of considerable interest because the factors causing the metamorphic changes from vegetable debris to coal of different rank will probably have been effective in much the same way in most coalfields, and because the large range in the rank of the coals makes South Wales important for any general theory of coal metamorphism.

Trotter reviews the most important of the theories already proposed to explain coal metamorphism—the heat of igneous intrusions (magmatic heat), difference in the composition of the seams before metamorphism (original deposition), the heat and pressure due to depth of burial beneath younger sediments (pressure of superincumbent strata), and the heat and pressure which caused or was caused by the folding and faulting of the coal measures (tectonic forces). He reasonably rejects the first of these theories because of the absence of intrusive rocks in or sufficiently near the coalfield. The second is equally unsatisfactory because the differences in rank are regional and not related to particular seams as they should be if differences in the composition of the original vegetable debris of individual seams were the cause of differences in the coals. The third explanation is rejected because the stratigraphic thickness of that part of the coal measures

that has been measured is less in the high rank than in the low rank part of the coalfield.

Having rejected the first three of the four explanations already proposed, Trotter is left with tectonic forces as the sole cause of coal metamorphism in South Wales. As the basis of his tectonic theory, he postulates a major thrust fault dipping at a low angle and becoming progressively deeper southwards in the direction of decreasing rank of the near-surface coal. This thrust is identified with a fault mapped at several places to the north of the coalfield, but its presence and position beneath the coalfield are based not on direct observation but on theory. He assumes that the percentage of volatile matter (on a moisture and ash free basis) in the coal at any particular point is proportional to the square of the distance of this point from the fault plane ; for example, at the fault plane itself the percentage is zero, at one unit of distance—one, at two units of distance—four, at three units of distance—nine, and so on. The length of the unit—about 2,000 feet—is calculated from several series of analysed samples collected from the upper 2,000 feet or so of beds, deeper beds not having been sampled.[1]

To have generalized a large number of coal analyses into such a simple mathematical result is an achievement of a kind rarely possible with geological data. But although his extremely simple square root relation fits the analyses reasonably well, it will be shown later that a significantly better fit is given by the slightly more complex logarithmic relation already applied to other coalfields. The apparent simplicity of his explanation depends entirely on the percentage of volatile matter at the thrust having the special value—zero. With relations different from the one he has adopted, the zero value may be at a very different depth (with the relations to be used later, zero volatile matter is at an infinite depth) and the thrust hypothesis has either to be abandoned or a less apparently plausible arbitrary value than zero adopted as marking the depth of the thrust. Nevertheless, Trotter's generalization, even if only approximate, has an importance which is quite irrespective of the theory which he used to explain it. Economically it has value because the rank of the coal can now be forecast in at least the upper part of the coalfield. The theoretical implications are no less important. If volatile matter is the same at all points equidistant from the thrust plane, the rate at which rank increases towards this surface—the metamorphic gradient—is the same at all

[1] In his paper Trotter has doubled the volatile percentage and used as his unit the distance in which the square root of this double value is increased by unity. For simplicity actual and not double volatile percentages have been used to illustrate his theory, his unit of distance "K" being altered accordingly from 1,450 feet to 2,050 feet.

parts of the coalfield. Hence the different kinds of coals—anthracite (4–10 V.M.), dry steam coals (10–13·5 V.M.), coking steam coals (13·5–23 V.M.), and coking coals (23–30 V.M.)—are each confined to shells of known thickness, each shell being parallel to the reference surface (thrust). Not the least important feature of Trotter's paper is the way in which he shows that the distribution of coals of different ranks is controlled by a surface less deformed than are the coal measures themselves. Geologically this can be interpreted only as meaning that metamorphism was later than deformation. Trotter himself considers the metamorphism to be due to the thrust and apparently considers that the beds were deformed prior to their being metamorphosed by the thrust movements. It will be shown later that the facts can be consistently explained in terms of depth of burial. This evenly dipping thrust is the very basis of Trotter's paper. Instead of considering the analysed samples with respect to the beds in which they occur and discussing the changes of rank in each seam, he has found it simpler to consider them with respect to this " thrust " surface, and in effect to neglect stratigraphy. That he is justified, is conclusively shown by his cross section (fig. 4), which shows a progressive decrease in rank away from the line representing the " thrust ", the decrease in rank being in the direction of decreasing age in the north side of the diagram only. The most critical part (the Graigola Seam at the Craig Cefn Parc Syncline) is shown even more clearly by means of an elegant diagram, fig. 7, where he has conclusively demonstrated that the complex isovol line pattern of this seam is due solely to the distance between the seam and the " thrust " surface. It is unfortunate that this successful approach was not followed through to include the whole coalfield, as could easily have been done by reducing all the analyses to the same datum plane, for example, either to a plane parallel to the thrust or preferably to sea-level. The means of reduction is provided by the gradients he had already established for the sampled vertical sections.[1] Metamorphism certainly post-dated deformation in parts of the coalfield but not perhaps over the whole. A critical test that might be applied to some parts would be the comparison of two coal samples from the same seam, one from the upthrow and the other from the downthrown side of a fault with a substantial throw, the two samples being as close to the fault as possible. If of the same rank, metamorphism took place prior to faulting, but if of different ranks, after faulting, the difference in rank corresponding to the vertical throw of the fault.

[1] According to Trotter's relation, if " H " the height above sea level, " V " the volatile content at height " H ", and " V_S " the volatile content at sea level, then $V_S = \left(\sqrt{V} - \frac{H}{2{,}050}\right)^2$.

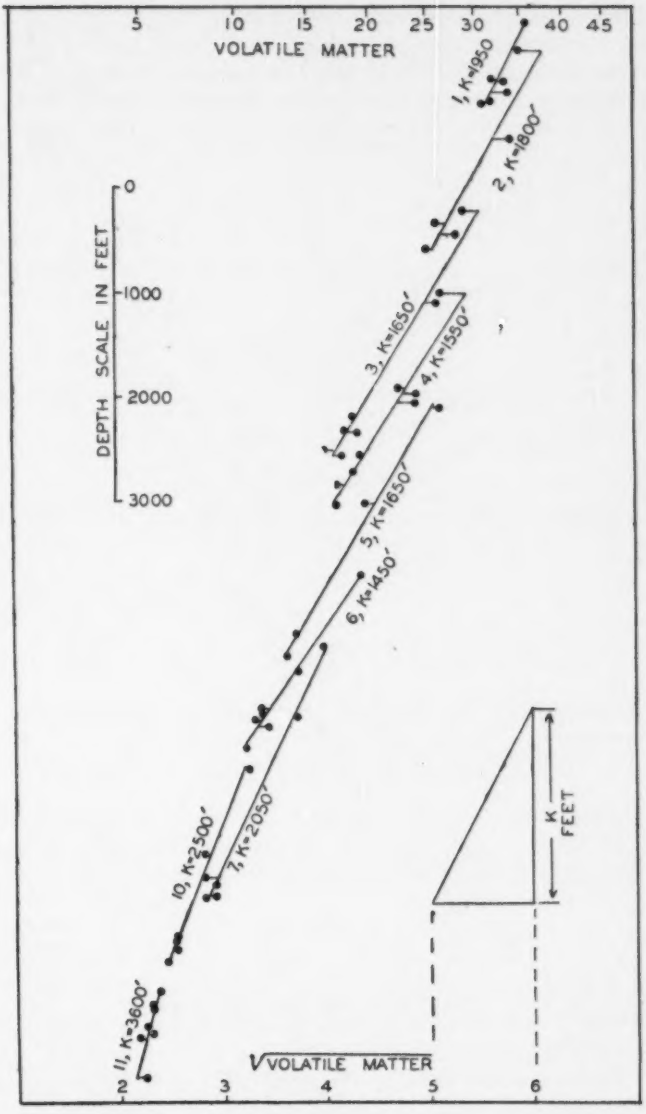
Vertical Gradients, Rate of Change of Rank with Depth

It is important to compare the gradients established by Trotter with those in other coalfields. When the range in ranks is the same the comparison is not difficult. For example, it is easy to show that the gradient in that part of South Wales with a volatile content of more than 14 per cent is the same (within the limits of error of observation) as that in the central part of the Kent Coalfield (Snowdown, Barfresdon, and Maydensole) (Dines, 1932), and considerably flatter (less metamorphic change per unit depth) than in the remainder of that coalfield. This comparison can be considered in terms of absolute decrease in volatile matter per 100 feet, in terms of the depth in which the square root of the volatile matter decreases by unity (Trotter), or in terms of the depth in which the logarithm of the volatile matter expressed as a percentage of fixed carbon decreases by unity (Wellman, 1948). On the other hand, when the range of ranks is different in the two areas no comparison is possible until one or other of the methods already proposed (or some new method) is accepted as a basis of comparison. The problem is considerably complicated by the fact that the gradient changes systematically within the Kent coalfield, and hence cannot be assumed to be invariable within *any* coalfield.

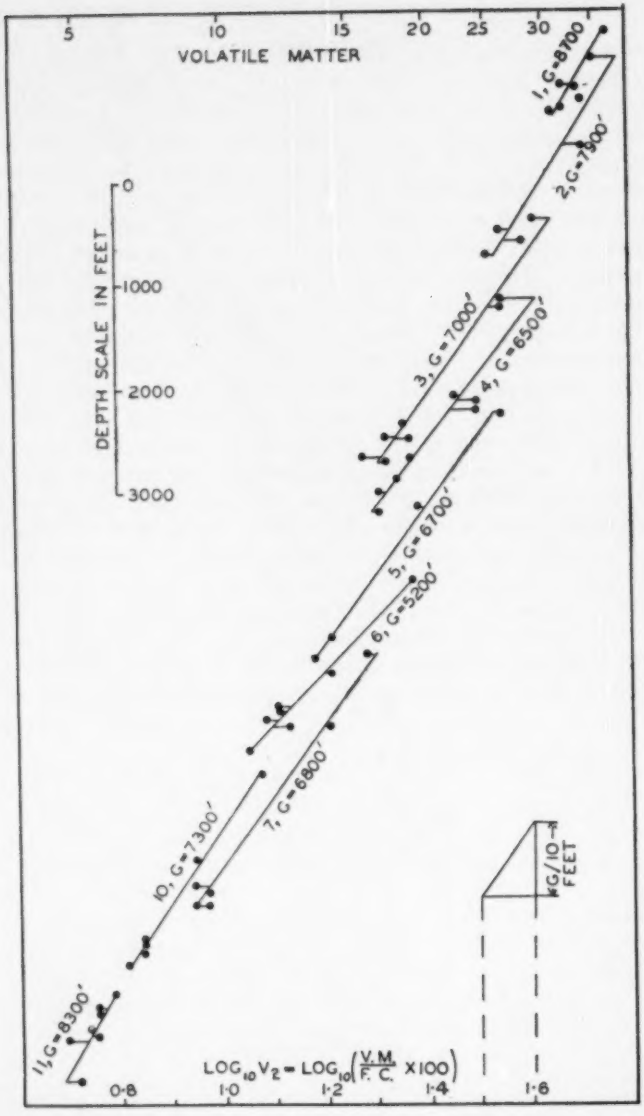
Trotter's square root relationship implies a uniform gradient over the whole coalfield but significant variations occur, especially in the high rank part. The following values (see Text-fig. 1A) were obtained by plotting the square roots of volatile content against depth in the nine columns with more than two analyses given by Trotter (pp. 409–412) :—

Trotter's Column Number	1	2	3	4	5	6	7	10	11
"K"	1,950	1,800	1,650	1,550	1,650	1,450	2,050	2,500	3,600
V.M. Range	31–36	25–35	17–29	17–26	13–19	10–14	8–16	6–10	5–6

The sections as arranged by Trotter, and as given above, are in order of increasing average rank. The gradients have not been calculated by least squares as the data did not appear to be uniform enough to make this worth while, but care was taken to give equal weight to all points by sloping and placing the gradient lines so that the squares of the errors were, as far as could be judged, at a minimum. It will be noticed from the above table that above 14 per cent volatile matter the gradients in terms of Trotter's unit of distance "K" are about 1,700 feet. Below 14 per cent the numerical values of the gradients progressively increase, rising to 3,600 feet in No. 11. But this last section shows considerable scatter, is only 800 feet thick, and cannot

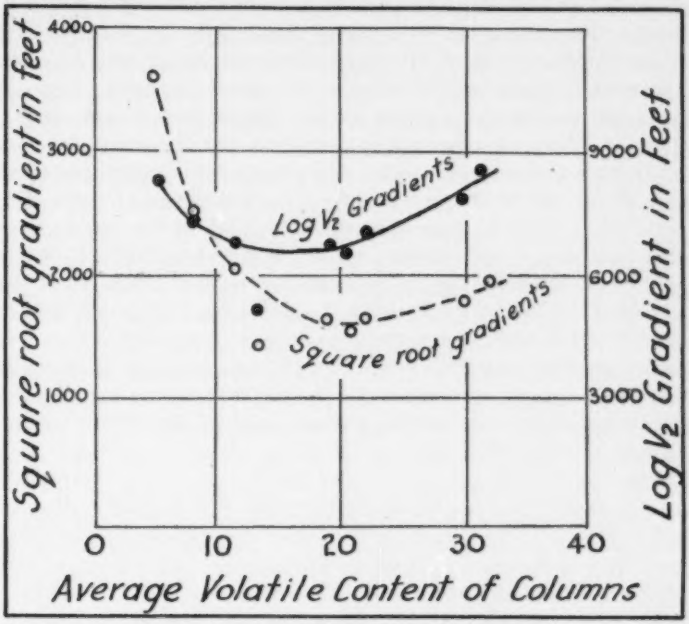


TEXT-FIG. 1A.—Relation between depth and square root volatile matter in South Wales bores and shafts. K = depth (in feet) in which square root volatile matter is reduced by unity.



TEXT-FIG. 1B.—Relation between depth and log V_2 in South Wales bores and shafts. G = depth (in feet) in which log V_2 is reduced by unity.

be considered reliable.[1] At first it might be thought that this increase in the numerical value of the gradient (flattening) represents a progressive change in the higher rank part of the coalfield similar to that at Kent. But by plotting the columns according to the logarithm of



TEXT-FIG. 2.—Graph showing relation between square root and log V_2 gradients and average volatile content of columns.

the volatile matter expressed as a percentage of fixed carbon (as I have done with Kent coalfield sections) these variations are much reduced and are only slightly greater than their probable error (Text-fig. 1B) :—

Trotter's Column Number	1	2	3	4	5	6	7	10	11
Logarithmic Gradient in Feet	8,700	7,900	7,000	6,500	6,700	5,200	6,800	7,300	8,300
V.M. Range	31–36	25–35	17–29	17–26	13–19	10–14	8–16	6–10	5–6

In order to compare the variations in the square root and the logarithmic gradients more closely, both values for each column with more than two analyses have been plotted against the average volatile content of that column (Text-fig. 2), the square root gradients being

[1] Trotter has accounted for a small part of the difference in Column No. 11 by considering the slope of the underlying thrust at this place to be 25°. When this slope is allowed for, the gradient becomes 3,250 feet.

shown by open circles and the logarithmic gradients by solid circles. With the exception of No. 6 (average 12 per cent), which is low, the gradients can be generalized by means of curves. Although the differences in the logarithmic gradients are small, their regularity suggests that they are significant, in spite of the fact that they only barely exceed the probable error, as indicated by the scatter of the plotted analyses in fig. 1. The variations in the square root gradients greatly exceed their probable error and are clearly significant. It should be noted that these two curves are not independent of each other—if one is defined the other can be calculated, and that the square root gradients are not reduced to a straight line even if an average value (straight horizontal line) is adopted for the logarithmic gradient. For practical purposes in order to calculate the rank of the coal at depth it is convenient to use a single gradient for the whole coalfield. When an average value is adopted for each method the differences in the calculated values are small except for anthracite. As an example of the differences within the anthracite range, my calculated values and the values calculated by Trotter (p. 412) are compared in the table below with the observed values for No. 10 (Dulais)—the highest rank reliable column. I have adopted the value of 7,200 feet for the average logarithmic gradient.

Depth Feet	Observed	Calculated Trotter	Diff. from Obs.	Calculated by Log. V_2	Diff. from Obs.
0	10·5	10·5	0	10·5	0
831	8·0	8·1	0·1	8·1	0·1
1,612	6·5	6·0	0·5	6·2	0·2
1,660	5·5	5·9	0·6	6·2	0·3
1,774	6·5	5·7	0·8	6·1	0·4
1,882	6·0	5·4	0·6	5·9	0·1
2,000	—	5·1	—	5·8	—
3,000	—	3·2	—	4·3	—
4,000	—	1·7	—	3·2	—
6,650 (thrust)	—	0·0	—	1·4	—

Both sets of differences are small in absolute value, being considerably less than those shown by many of the lower rank columns. But when considered as a ratio of the percentage of volatile matter, as they should be, the largest of Trotter's differences is 14 per cent of the observed values and greater than the percentage difference in the lower rank columns, most of which show considerably more scatter than does this column. In my calculated values the differences are reduced by half, the reduction in error being clearly significant. In the table both sets of calculated values have been extended down below the limits of observation in order to show their progressive deviation with depth. In view of a possible difference between the gradient of

this high rank column and that of the coalfield average as in Kent coalfield this column does not prove that the logarithmic method of calculation is the more accurate. A conclusive test would be provided only by a deep bore that penetrated bituminous coal as well as anthracite. But it is unfortunate that no single bore is known deep enough, and these alternative methods have to be tested from more general evidence. The degree of association of coals of different ranks in other parts of the world, at or near the ground surface, provides a rough test. In areas where coals of different ranks are exposed, the metamorphic shells have been truncated by the ground surface. Faults have interrupted these shells at many places, but on the average the greater the vertical interval between coals of different ranks the greater will be the horizontal distance between these coals when exposed by erosion, the relation being exactly the same as that by which the relative thicknesses of adjoining and conformable formations can be judged by comparing their outcrop area on a map. According to Trotter, the distance between coal with 4 per cent and coal with 0 per cent volatile matter (in effect graphite) is about 4,000 feet and the same as the distance between coal with 4 per cent and coal with 25 per cent. An association of coals with 4 per cent volatiles and those with 25 per cent is known from many areas and is sufficiently close to be in keeping with an interval of about 4,000 feet. But the degree of association of graphite and 4 per cent anthracite is far less close, and this suggests that the interval between them is much greater than 4,000 feet. If the logarithmic gradient is adopted, 0 per cent volatiles is a limiting value which is never reached, hence, by this measure of gradient, the horizontal distance between graphite and 4 per cent anthracite will be enormously great, as, in fact, it is found to be. This general argument tends to show that the logarithmic gradient more closely corresponds to the limited data available than does the square root relationship adopted by Trotter.

The Implications of Thrust Metamorphism

The concept of a thrust underlying the coalfield is as satisfactory as any other if the thrust is used merely as a reference surface from which to calculate the rank of the coal. Moreover, provided that no other consistent explanation can be found, a strong argument will exist for the thrust. But it will be shown later that such an alternative explanation is available. Meanwhile, some general disadvantages of the thrust hypothesis will be mentioned. Probably because his thrust is postulated to be beneath the coal measures, Trotter makes no mention of the metamorphic conditions on the lower side of the thrust. However, it cannot be supposed that thrusts, if effective, are effective

only in South Wales, or that thrusts at all places are below rather than within coal measures. Consequently, according to Trotter, it would be expected that thrusts and other faults, in a degree more or less proportional to their displacement, will have a decided metamorphic effect when they dislocate coal measures. The most striking effect should be immediately beneath such faults, where coal rank should decrease downwards, that is in a direction opposite that expected from Hilt's Law. Evidence for such negative gradients would do much to demonstrate the metamorphic effectiveness of faults, but as far as I am aware none has been proved. Such negative (reverse) gradients are quite different from the effect of thrusting after metamorphism, when high rank rocks are thrust over lower rank ones, the vertical metamorphic gradient then being repeated but not reversed.

Another difficulty is brought out when the South Wales coalfield is compared with other coalfields in which no thrusts have been postulated. Hilt's Law (decrease in volatile content with depth, as in a bore) is generally accepted for bituminous and anthracite coalfields and an analogous decrease in moisture content with depth is known from sub-bituminous and lignite coalfields. These changes can most easily be explained as being due to the progressive increase in temperature and pressure with depth at the time of deepest burial. Thrusting, if effective as a metamorphosing agent, must have caused an increase in the rank of the coal near the thrust when the thrust movement took place, and hence must have caused the rate at which rank decreases upwards away from the thrust to become more rapid (steepened the vertical metamorphic gradient). Consequently, if a metamorphically effective thrust actually underlies South Wales the vertical metamorphic gradient should be steeper there than in coalfields where no such thrusts exist. But the vertical gradient in the lower rank part of the South Wales coalfield is the same as at the centre of, and very considerably less than at the margin of the Kent Coalfield. Moreover, in the high rank part of the South Wales coalfield (the part nearest the thrust) the gradient is either slightly flatter than in the lower rank part or considerably flatter, dependent upon whether the gradients are measured by the logarithmic or by the square root method. The often given gradient of 6 per cent decrease in volatile matter per 1,000 feet (Millott, Cope, and Berry, 1946, p. 39) for coalfields with 25 to 35 per cent volatile matter is also in substantial agreement with the South Wales values. Hence, the value of the vertical metamorphic gradient at South Wales is no greater than at many other coalfields and considerably flatter than at parts of the Kent coalfield. Consequently, the thrust has not steepened the gradient as compared with other coalfields where no thrusts have been postulated.

Perhaps it might be argued by those who favour thrusts that all regional high rank coal is due to thrusting and that without such thrusting the volatile content will not be reduced below 50 per cent. In many places, as for example the Appalachians, coal rank at the ground surface increases in the direction of increasing deformation (Campbell, 1930) but this does not mean that the gradient steepens in this direction, but merely that the lower rank shells still preserved in the less deformed areas have been eroded from the more deformed. In order to prove that thrusting is metamorphically effective it has to be shown that the rate at which rank increases with depth is more rapid in the deformed than in the less deformed areas (that the metamorphic shells are thinner), but this has not been proved and indeed the reverse is probably the case in many places. If the gradient is no steeper in the deformed than in the less deformed regions, then the thickness of the now eroded metamorphic shells must have been equally as thick as those in part still preserved in the less deformed regions. If thrusting does nothing to reduce the necessity of postulating a thickness of overburden in conformity with the gradient and the surface rank, thrusts are non-effective ; and regional coal metamorphism has to be explained as being due solely to the temperature and pressure caused by depth of burial. This conclusion can be avoided only by considering that coal was (and is being) metamorphosed to high rank at the actual ground surface or by postulating an equally unlikely sharp steepening of the gradient in the eroded beds.

The validity of this general argument based on metamorphic gradients is shown by comparing regional coal metamorphism with the special coal metamorphism due to the heating effects of igneous rocks. An invariable feature of such contact metamorphism is the way in which the metamorphic gradient is steepened ; the closer the coal to the intrusion, the more does its rank differ from near-by coal from the same stratigraphic horizon not affected by the intrusion. Moreover, negative gradients are well shown on the lower side of intrusive sills, the rank of the coal decreasing downwards at a rapid rate until beyond the influence of the intrusion and then gradually increasing in rank according to Hilt's Law. If thrusts (and other large faults) cause metamorphism of coal, effects similar to those caused by igneous rocks should be conspicuous in many faulted coalfields ; that they have not been reported, in spite of large faults being not uncommon, shows that faults are non-effective or at the most far less effective than the smallest igneous intrusion.

Trotter's Objections to Metamorphism by Depth of Burial

Having shown that the thrust explanation meets with difficulties when the thrust is considered other than merely as a reference surface,

an attempt will now be made to explain the distribution of coals of different ranks in terms of depth of burial. But first Trotter's objections to depth of burial have to be considered. After giving the thickness of the Lower Coal Series in different parts of the South Wales coalfield and showing that the increase in the rank of the basal seams bears no relation to the increase in thickness of this series, Trotter (p. 391) states :—

"If 5,000 feet of additional strata have made no appreciable difference to the volatile content of the gas coals on the southern crop, and devolatilization from south to north takes place in the direction of thinning of Coal Measures strata, then the additional thickness of post-Carboniferous sediments required in the north-west, as compared with south-west, to effect a drastic reduction from gas coals with a volatile content of 30 per cent to a high-ranking anthracite with a volatile content of 4 to 6 per cent must have been so vast as to be beyond the bounds of possibility, for it must have been tens of thousands of feet ; in fact, the necessary adjustment due to the great thickening of geosynclinal strata would have caused the basal upper Carboniferous rocks to dip northwards towards the anthracite area, whereas they lie in an east-and-west syncline with steep regional southerly dips in the anthracite area. Thus, we may also dismiss Bailey's suggestion (1944) that the anthracitization was caused by superincumbent Permo-Carboniferous sediments presumed to be present in the north, but absent in the south, and now completely removed by denudation."

Two essential points are made by Trotter :—

(1) That the sediments now preserved do not increase in thickness in the direction of increasing rank.

(2) That if the high rank part had once been covered by thick overburden, the dip of the Upper Carboniferous beds would still be towards the area of deepest burial.

The first is a real difficulty only if the sediments that caused the increase in rank rested conformably on those that are now preserved. But if the bulk of the overburden was deposited after deformation of the coal measures there is no need to suppose that such overburden would have thickened in the same direction as the preserved coal measures do. To explain the change in rank by such unconformable overburden would be as fanciful as introducing a hypothetical thrust if it were not that Trotter has himself provided evidence for unconformity. By showing that the coal rank distribution can be explained in terms of a surface less deformed than the beds themselves he has shown that the beds were metamorphosed after they had been

deformed. If metamorphism is due to overburden then this overburden must have been unconformable to the coal measures.

The second point presents no difficulty in New Zealand where conclusive evidence exists that a thickness almost as great as that required to have been eroded from the South Wales coalfield since the upper Palaeozoic has been eroded from the Paparoa Range since the mid-Tertiary (Gage, 1949 ; Wellman, 1949), the important feature being that the average dips are now away from and not towards the once more deeply buried part. At the time of maximum deposition in South Wales what is now the ground surface would have sloped towards the anthracite area, the dip of the basal coal measures being correspondingly more northerly than at present. The present dip of the coal measures is partly due to differential uplift which caused (or was caused by) the erosion of the unconformable cover. During this uplift the basal upper Carboniferous beds (coal measures) were progressively tilted away from the anthracite area so that when they became exposed at the ground surface their dip was very different from that at the time of maximum subsidence. That mountain ranges often rise from areas where thick sediments accumulated rapidly is a commonplace of geology, and it is consequently not surprising that uplift should follow after the almost certainly rapid deposition of the thick cover on the anthracite area.

Metamorphism by Depth of Burial

In this paper no good purpose would be served by considering all the refinements required to estimate reliably the total thickness of overburden above the highest rank coal now exposed (4 per cent volatile matter). It will be sufficient if it can be shown that this thickness was not less than 18,000 feet, the addition of a few thousand feet to this minimum making little difference to the general argument for metamorphism by depth of burial. Trotter has shown by an analysis of the coal analyses, as a first approximation, and up to a value of 36 per cent, that the square root of the volatile content increases by unity for every 2,000 feet away from the plane of the " thrust ", and hence that the distance from a sample with 4 per cent volatile matter to one with 36 per cent is about 8,000 feet. It is true that no single bore has penetrated for this full depth and proved it, but when dealing with stratigraphic thicknesses geologists make estimates, and often extremely accurate estimates, by combining a series of relatively thin surface columns into a composite column many thousands of feet thick. The analogy between metamorphic shells and sedimentary formations is extremely close. Both can change rapidly in thickness when traced horizontally, and such changes often render inaccurate thick composite columns. The amount the difference in gradients is likely to cause the

metamorphic shells to change in thickness at South Wales has already been discussed in some detail, it being shown that no evidence exists that these shells were thinner above the high rank than above the low rank part of the coalfield. Consequently, 8,000 feet is accepted as the minimum distance between 4 per cent and 36 per cent volatile matter. Trotter extended his square root relation up to coal with 49 per cent volatile content, assuming that this distance also would be about 2,000 feet. This has also been adopted, but merely as a convenience, it being almost certain that this interval will be considerably greater. Pie Rough (Millott, Cope, and Berry, 1946, p. 39) and Greymouth coalfield, New Zealand (N.Z. Geological Survey Bull. No. 45, in the press) both show that the rate at which volatile matter on a dry ash free basis decreases with depth is extremely slow in low rank bituminous coals. Thus, the value of 2,000 feet that has been adopted is unlikely to be an over-estimate. Consequently, the total distance from 4 per cent to 49 per cent is unlikely to have been less than 10,000 feet at South Wales and may well have been a few thousand feet greater.

Although Trotter has considered only those coals with a volatile content of less than 50 per cent (bituminous and anthracite), the thickness of the lignite and sub-bituminous shells has also to be considered. Perhaps owing to the absence of thick sub-bituminous coal measures from the British Isles, little attention has been given there to the considerable thickness represented by beds of these ranks in other parts of the world. In New Zealand the bulk of the upper Cretaceous and lower Tertiary coal measures are sub-bituminous, bituminous coal of these ages being restricted to the deeper parts of what were once narrow geosynclines filled with thick lower and middle marine Tertiary beds (Wellman, 1949) (Gage, 1949), and which are best represented on the west coast of the South Island. The marine Tertiary beds are richly fossiliferous and have been closely divided (Finlay and Marwick, 1947). In the sub-bituminous areas the total Tertiary thickness does not exceed 5,000 to 6,000 feet but in the bituminous areas the thickness is considerably greater. The rate at which the individual divisions thicken towards the geosynclinal axes indicates the total thickness of marine beds above the highest rank coal (low volatile bituminous) to have been about 12,000 feet, but owing to erosion from the mountain ranges that now represent these everted geosynclines, this total can only be estimated. By a fortunate accident the Notown bore was drilled near the centre of an upper Tertiary and non-everted geosyncline between two of the everted lower Tertiary geosynclines. This bore reached a depth of nearly 7,000 feet and penetrated two different groups of coal measures. The lower, near the bottom of the bore, contains coal with about 50 per cent volatile matter and of about the same rank as the lowest rank coal measures

considered by Trotter.[1] The highest beds in this bore, Pliocene in age, contain woody lignite, and are unlikely to have been buried much more than 1,000 feet. The information provided by this bore is in agreement with the more general information from other parts of New Zealand and indicates that the lowest rank bituminous coal was buried to a depth of about 8,000 feet. Before adding the thickness of the lignite and sub-bituminous shells determined from the Notown Bore to the thickness of the bituminous and higher rank shells at South Wales to give the total depth of burial there, it has first to be shown that the metamorphic gradients are not widely different at the two places. Unfortunately, there is no overlap of coals of the same rank at the two places and no direct comparison can be made. It can be shown that the gradient in the bituminous coal measures at Greymouth is not far different from that in the low rank part of the South Wales coalfield, and judging from the marine stratigraphy it is very probable that a thickness equal to that penetrated by the Notown Bore once covered the lowest rank bituminous coal at Greymouth. Moreover, although it is known that metamorphic gradients vary considerably in coals of bituminous rank, gradients may not have

[1] The following are the proximate analyses of coal samples from the Notown Bore :—

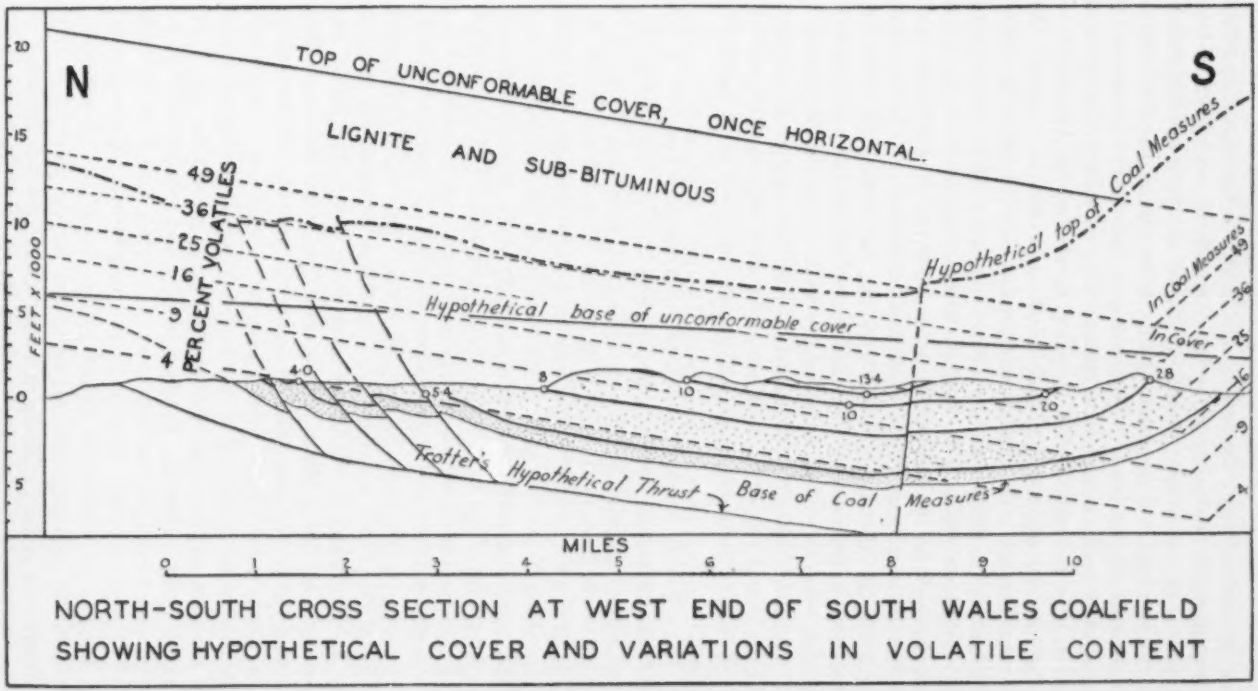
	M.	*V.M.*	*F.C.*	*Ash.*
3,000 feet. Selected sample .	23·0	30·0	38·5	8·5
6,893 feet. Selected samples .	4·1	45·2	44·5	6·2
	3·2	44·3	42·5	10·0
	4·5	45·6	43·1	6·8
Calculated equivalent rank coal of English type at 6,893 feet .	*9·0*	*40·0*	*51·0*	—

The adopted comparison of the coal from the bottom of this bore with the hypothetical coal with 49 per cent volatile matter postulated by Trotter is not exact, but an accurate comparison of ranks is almost impossible. In order to make such a comparison the type of the two coals has to be taken into account. English coals in general are less canneloid, and have, rank for rank, a higher ratio of fixed carbon to volatile matter than have New Zealand coals. From a study of the variation in the composition of coals of different types but of the same rank (*N.Z.G.S.* Bull. No. 45 in the Press), it is possible to calculate that the composition of a coal of average English type at the bottom of the Notown bore would be about M. = 9·0 ; V.M. = 40·0 ; F.C. = 51·0. This gives 44 per cent volatile matter on a moisture-free basis and is somewhat higher in rank than the 49 per cent coal with which it is compared. On the other hand it has already been shown that the rate at which volatile content changes with depth between 36 and 49 per cent is considerably slower than postulated by Trotter. From the average values of the Pie Rough analyses it was found that the vertical distance between an English coal with 36 per cent volatile matter and one with 44 per cent volatile matter and 9 per cent moisture is about 3,000 feet, and about a thousand feet greater than the value adopted here. The validity of the above argument depends on the gradient being about the same at Pie Rough as at South Wales. Extrapolating the average value of the Pie Rough moisture free volatile content from 36 to 25 per cent gives a 2,000 ft. vertical interval and the gradient is cons quently not far different from that at South Wales.

varied to the same extent in lower rank coals where metamorphism is chiefly a matter of compaction and the expulsion of moisture. This change may depend more on rock pressure, which would have been substantially the same at the same depth in all areas at the time of deepest burial, than on the geothermal gradient, which is likely to have varied as much from place to place in the past as it does to-day. This uniformity of low rank gradients is not easy to prove, there being little published data dealing with metamorphic gradients in lignite and sub-bituminous coal measures in spite of the fact that coal measures of these ranks must many times have been penetrated by deep bores. But what little evidence there is from other parts of the world agrees fairly well with that from the Notown Bore, making it reasonable to assume that all bituminous coal has been buried to a depth of not less than 8,000 feet. This 8,000 feet has to be added to the 10,000 feet already considered to give a total depth of burial of 18,000 feet for the 4 per cent anthracite.

How that Cover may have been Deposited

The postulated thickness of overburden across the north–south section already illustrated by Trotter (p. 396) at the west end of the South Wales coalfield, is shown by Text-fig. 3. In order to show the thickness of overburden correctly with respect to the width of the coalfield the vertical and horizontal scales are made the same in my cross section. The volatile percentages given by Trotter in his section have been used to define the position of the 4, 9, 16, and 26 per cent volatile lines, a distance of 2,000 feet being adopted for the two intervals up to 49 per cent, and a thickness of 8,000 feet for the thickness of the lignite and sub-bituminous shells. The equal-metamorphic-surfaces are shown as being parallel, possible systematic variations in the gradients being neglected. It will be noticed that except for rank variations due to differences in altitude, the surface rank and the postulated thickness of overburden above the present ground surface progressively decrease towards the south end of the cross section. At the extreme south end the equal-rank surfaces are shown sloping steeply upward parallel to the coal measures, the rank at the ground surface being considered to increase rapidly to the south. This is meant to represent the slight but consistent increase in rank shown by Trotter's fig. 1 south of a line joining Swansea and Cardiff. According to the depth of burial hypothesis adopted in this paper this increase represents a thickening of cover in this direction. It has already been shown that over at least part of this cross section the upper part of the cover is unconformable to the coal measures. The southerly increase in rank is interpreted as being due, not to the increase in the thickness of this unconformable cover, but to the increase in thickness


N
S
TOP OF UNCONFORMABLE COVER, ONCE HORIZONTAL.
LIGNITE AND SUB-BITUMINOUS
PERCENT VOLATILES
49
36
25
16
9
4
FEET X 1000
20
15
10
5
0
5
Hypothetical top of Coal Measures
Hypothetical base of unconformable cover
In Coal Measures
In Cover
Trotter's Hypothetical Thrust
Base of Coal Measures
40
54
8
134
10
10
20
28
16
9
4
MILES
0 1 2 3 4 5 6 7 8 9 10
NORTH-SOUTH CROSS SECTION AT WEST END OF SOUTH WALES COALFIELD
SHOWING HYPOTHETICAL COVER AND VARIATIONS IN VOLATILE CONTENT

TEXT-FIG. 3.

of the coal measures themselves, due largely to the increasing stratigraphic depth and partly to the increase in thickness known to take place in this direction. According to this interpretation the line of minimum rank will represent the line where a minimum thickness of sediments accumulated. To the north the unconformable cover thickened, to the south the coal measures. By showing the hypothetical limits of these beds of different ages, an attempt has been made to illustrate this concept more fully in the cross section. As this one section is meant to represent conditions at two different times in the past as well as the present day it is necessarily complex. The adopted position for the top of the coal measures on the south end is based on the thickness of cover corresponding to the minimum surface rank at the line of section. To the north the total thickness of coal measures is made to decrease in conformity with the decrease in thickness known from the coal measures still preserved. For the sake of completeness and in order to show conditions immediately prior to the deposition of the unconformable cover, a line marking the hypothetical position of the base of this cover is shown on the cross section. The position of this line cannot be defined and is not considered to be accurately placed.

The following is a brief outline of the metamorphic history of this coalfield as represented by this cross section. At the end of coal measures times (perhaps the end of the Carboniferous), the depth of burial of the lowest coal seam progressively increased southward, the volatile content of coal at the base of the coal measures decreasing from about 36 per cent at the north to about 16 per cent at the south. (The equal rank surfaces for this period have not been shown except at the extreme right hand side.) The coal measures were then folded, the thick sediments to the south beyond the end of the section being more elevated than those to the north. Erosion followed deformation, the rocks to the south beyond the end of the section being more elevated than those to the north. After this deformation and erosion, or more probably at about the same time, the northern part was depressed by tilting along an east-west line. The depression then formed was immediately filled by sediments, possibly Permian, which were likely to have been derived from the elevated area to the south. The conditions at the end of this period of sedimentation are shown by the cross section, if the sloping line that represents the top of the cover is made horizontal. Rapid depression and sedimentation at the north soon buried the coal measures more deeply than they had been in coal measure times. They were thus progressively metamorphosed by increase in temperature caused by the rise of the iso-geotherms through the subsiding coal measures and by the increase in load pressure, the present rank being reached after the full thickness of

cover had accumulated. This second period of metamorphism obliterated the early metamorphics pattern in which the metamorphic shells closely paralleled to the bedding planes and replaced it by the present one, in which, in part at least, the metamorphic shells are less deformed than the coal measures and discordant to the seams. To the south conditions were different, the coal measures had been thicker than to the north and having been more deeply eroded a greater thickness of unconformable cover was required to increase their rank. The cover did not reach this required thickness and their rank was not increased. They should consequently still show a metamorphic pattern that is related to the bedding of the coal measures. The elevation that followed was again proportional to the preceding subsidence, the part with the greatest thickness of unconformable cover at the northern end of the section being more elevated than the southern part with less cover. The erosion that followed this period of elevation stripped off not only the whole of the unconformable cover but also some of the coal measures to expose the section as it is known to-day.

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Pre-Cambrian Algal Limestone in Western Australia

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(PLATE XV)

ABSTRACT

Stromatolitic structures in the late Pre-Cambrian Yandanooka Series of Western Australia have been identified as calcareous algae of the genus *Collenia*. They are the first organic remains recognized in the Pre-Cambrian of this State. Distribution of the sediments containing these algae has been traced over 200 miles between Perth and Yandanooka. Erratic blocks of this material occur in the Permian tillites.

CALCAREOUS algae occur in many Pre-Cambrian rocks, but have not been recognized before in Western Australia, which has an extensive development of Pre-Cambrian.

For many years certain erratic blocks in the Nangetty Tillite of the Permian in the Irwin River Basin (lat. 29° S., long. 115° E.) were suspected of having been originally calcareous algal colonies. These blocks are found in every stage of alteration from a crystallized stromatolitic limestone, with successive replacements, in layers, to a banded quartzite (see Clarke, Prendergast, Teichert, and Fairbridge, 1950). Dr. Teichert (personal communication) has recently found similar erratics in the Permian Lyons Tillite, some 300 miles north of the Irwin River Basin. The origin of these erratics had never been found, although it was presumed that they were Pre-Cambrian in age.

ALGAL ROCKS *in situ*

As the result of a specific search carried out in August, 1929, these stromatolitic algal limestones were found *in situ* by the writer and his senior students in the late Pre-Cambrian Yandanooka Series (of Woolnough and Somerville, 1924), which occupy a more or less continuous belt of outcrops extending from Yandanooka to south of Moora, a distance of over 100 miles. From the palaeogeographic point of view, it is interesting that this belt lies directly south of the glacial deposits in the Irwin River Basin and tends to confirm the impression that the Permian ice movement in this region was from south to north.

The stromatolitic algal rocks found *in situ* are, without exception, completely altered to quartzites now, and none were found like those in the glacial erratics where the limestone was partly or wholly preserved. Numerous thin sections of the latter have been made but none have disclosed any cellular structure. The stromatolitic (banded) structure in the quartzites found *in situ* is, on the other hand, often exceptionally well preserved.

Photographs of the material were submitted to Professor T. Harlan Johnson, of the Colorado School of Mines, who was able to confirm

that the specimens belong to the genus *Collenia* and further study may perhaps enable him to allocate a specific name to them.

Associated with the stromatolitic quartzites, both in the tillite blocks and in the Yandanooka outcrops, are beds containing remarkable intraformational breccias. They are likewise completely replaced by silica, but may originally have been limestone or possibly dolomitic, since they are reminiscent of certain dolomitic intraformational breccias. The possibility of a brecciated chert might also be considered. Individual fragments are mainly about 1–3 cm. long and ½ cm. thick, scattered at all angles through the breccia beds. They are not rounded or curled at all like those generally found in clay-pellet breccias. The latter are very common in the late Pre-Cambrian of the Adelaide Series in South Australia (Howchin, 1910), but exactly similar intraformational breccias do not appear to be known there.

Distribution

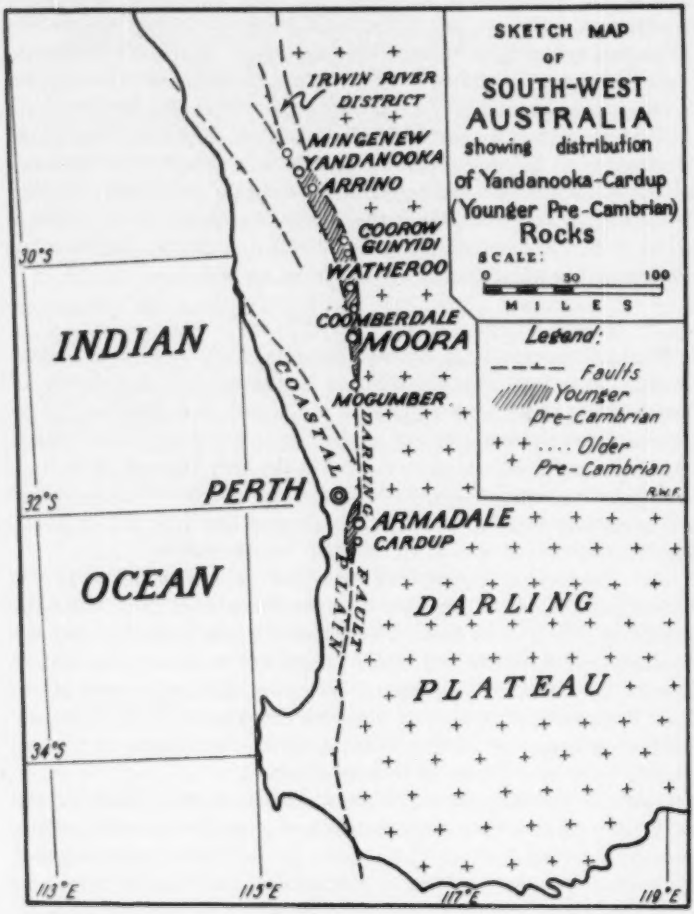
The localities where the stromatolitic algal rocks and the associated breccias have been found *in situ* are as follows: in the vicinity of Yandanooka, in the area north-west of Gunyidi near milepost 157 on the main road south of Coorow, in the hills south-east of Coomberdale (especially at the ballast quarry), and in the area just east of Moora. A little farther south, north of Mogumber, Woodward (1915) described a " banded carbonated chert-rock ", sheared and replaced by silica, which sounds rather similar to the other representatives.

This distribution corresponds with the general outcrop of the Yandanooka Series, a sequence of rocks which have been very little studied or explored to date. One reason for this neglect is that the exposures are generally very poor. The outcrops border the western edge of the older Pre-Cambrian granites and granite-gneisses of the West Australian Plateau, and are probably cut off from it by the northern extension of the great Darling Fault which forms its western boundary for over 500 miles (Jutson, 1934).

Since the Yandanooka rocks are mainly softer than those of the old granite plateau, they are very much worn down and obscured by the debris coming from it. This erosion probably went on throughout the Palaeozoic, when the region was continental. During Mesozoic times this deeply eroded border became completely covered over by continental and marine deposits, and only in late Tertiary and Quaternary times is erosion beginning to re-expose the tops of the old hills of Yandanooka rocks. Bores for water in the Mesozoic valley-filling beds, however, often disclose Yandanooka rocks in this belt at depths down to 200 or 300 feet.

Deep continental weathering of the surface of the Yandanooka rocks has thus been going on throughout the Palaeozoic era, at times during

the Mesozoic, and again in the Tertiary. It is accordingly not surprising that all rocks in any way soluble in character have been silicified or even completely replaced by silica.



TEXT-FIG. 1.—Sketch-map of South-West Australia, showing distribution of Yandanooka-Cardup (Younger Pre-Cambrian) rocks.

THE CAVE FORMATIONS

Some attempt has been made to find a locality where the extreme silicification of the algal and breccia beds has not taken place, but with only limited success. A number of caves have long been known

in the belt of the Yandanooka rocks, and in one of the more accessible of these, 6 miles south-west of Coorow, at about 860 feet above the sea-level, an excellent exposure of the shaly facies was found. The dip is about 7–10° W. and after a narrow, partly collapsed opening, the cave was found to open out along a band 10–20 feet thick, which had apparently been dissolved out to form a series of branching tunnels many hundred yards long.

The " shale " is a siliceous claystone, well-banded and flaggy. It discloses numerous small slump structures, 1 to 3 inches high, indicating original intraformational sliding from the east and north-east. A few thin joint planes and minor normal faults are filled with chalcedonic silica, and where erosion has removed the shale large sheets of it are left like curtains only about $\frac{1}{8}$ in. thick. Here and there a hollow box-work of this silica is preserved, inside which the rock has been entirely removed save for a little deposit of soft clay dust on the floor of the " boxes ". The whole floor of the cave is covered by about 10 feet of this choking dry dust. The cave is perfectly dry and marsupials which have fallen into it have become completely mummified.

There is no trace of limestone in the shale, nor of karst features or travertine in the cave. The surface crusting of the shale is by silicification only. It is therefore very puzzling to explain the removal of this extensive zone in the shale by solution. It is suggested, quite tentatively, that the shale originally contained gypsum or some similar evaporite salt, and that it was the removal of this soluble material by water during the pluvial periods of the Pleistocene that originally produced the cave. The soft, floury dust left behind is typical of that left in the Irwin River area to-day where a gypseous shale (Holmwood Formation) is weathering.

If this hypothesis is correct and an extensive evaporite shale formation once existed in the Yandanooka Series, it would find an interesting analogy in the late Pre-Cambrian of South Australia, where in the middle of the sequence there is evidence of an extended period when evaporites (mainly dolomite and magnesite) were being laid down (Mawson, 1941*b*, 1947). These are often brecciated and contain intraformational conglomerates.

Reports of other caves in the Yandanooa belt of sediments suggest that they are of similar nature. Campbell (1910) described one also from near Coorow (4 miles south-west) which slopes down at 30° in silicified fine-grained sandstone, and he gave a sketch of " silicification layers " which is clearly identical with one of our *Collenia* algal structures. He also found thin sheets or filaments of chalcedony in the joints. Another cave, Jingemia, situated 5 miles north-west of Watheroo about 27 miles to the south of Coorow, was described by

Woodward (1912). This is marked on old maps as " extinct volcano, 70 feet deep ", but Woodward reported " contorted quartzites ", dipping 10° south-west, associated with a hard crystalline limestone ; he believed that solution of the latter produced a collapsed sink-hole.

Correlation

In the type area of the Yandanooka Series (Campbell's " Quartz Conglomerates and Submarine Tuff ", 1910), the sequence consists of a thick succession of purple tuffaceous shales, current-bedded gritty sandstones, quartz conglomerates, and these stromatolitic and breccia-bearing quartzites (originally limestones). They are probably up to 3,000 feet in thickness, but although they are Pre-Cambrian in age, they are not metamorphosed at all. They have not been severely folded, but are regionally tilted to dip 20° to 35° E.N.E. in fault blocks, towards the main Darling Fault. They have not been intruded by granites and only locally are affected by younger basic dykes ; some of which near Arrino are associated with lodes of copper carbonate (Campbell, 1910).

As indicated above, this belt may be followed from Yandanooka to Moora, and perhaps a little farther south, after which it disappears finally beneath the Mesozoics (see map by Campbell, 1910, and short notes by Blatchford, 1912 ; Woodward, 1912, 1915, and Ellis, 1936). However, in the vicinity of Perth, another sequence of late Pre-Cambrian shales and quartzite appears, faulted along the western side of the Darling Fault. This is the Cardup Series (Prider, 1941) and is regarded by him as of Proterozoic age (Prider, 1948). These rocks are also penetrated by younger dykes and a few miles south of Cardup, at Mundijong, are cut by a silver-lead lode (Montgomery, 1908).

It is now possible to identify a calcareous algal fossil (also of the *Collenia* type) found by Prider in the quartzite at Armadale Brick Quarry. There are no equivalent intraformational breccias or tuffs, but, on the other hand, the group lies in an identical structural position and exhibits identical west slipping slump structures and a volcanic flow (which might correspond to the Yandanooka tuff). Its thickness is probably in the region of 3,000 feet.

The sedimentary and structural " picture " all along the western edge of the plateau thus suggests a marginal geosynclinal environment in late Pre-Cambrian times, which would be in harmony with the evidence of algal reefs, intraformational brecciation, and contemporaneous slumping by gravity on steep slopes, while the sediments contain the tuffs of contemporary volcanoes.

A very similar lithologic sequence (chocolate to purple shales, quartzites, dolomites, and limestones) in the unmetamorphosed Proterozoic rocks (Pertaknurra Series) of the Macdonnell Ranges in

Central Australia also contains abundant algal remains (Mawson and Madigan, 1930 ; Madigan, 1932). Here they were first found forty years ago by Chewings and identified by Howchin (1914) as *Cryptozoön*. In discussing their character, however, Madigan (1932) indicated that they corresponded closely to Walcott's *Collenia prolifica*.

In the Flinders Ranges of South Australia the Adelaide Series contains very similar algal material, in a sequence associated significantly enough, with intraformational breccias and conglomerates and again a very similar lithology (Mawson, 1925, 1941*a*, 1947, etc.).

Thus, with large gaps, one may possibly follow this younger Pre-Cambrian sequence over a distance of over 2,000 miles, which provides support for the correlation suggested by Prider (1948). One may readily perceive that such a long-distance connection could not be made on algae alone, but the coincidence of the brecciated limestones and dolomites, with intraformational breccias and conglomerates, of the evaporite rocks, of the purple tuffaceous shales and scattered volcanics, etc., lends colour to the argument.

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EXPLANATION OF PLATE

FIG. 1.—Calcareous alga *Collenia* replaced by silica, from near Gunyidi. (*Photo* : R. W. F.)

FIG. 2.—Detail of *Collenia* structure. (*Photo* : R. W. F.)

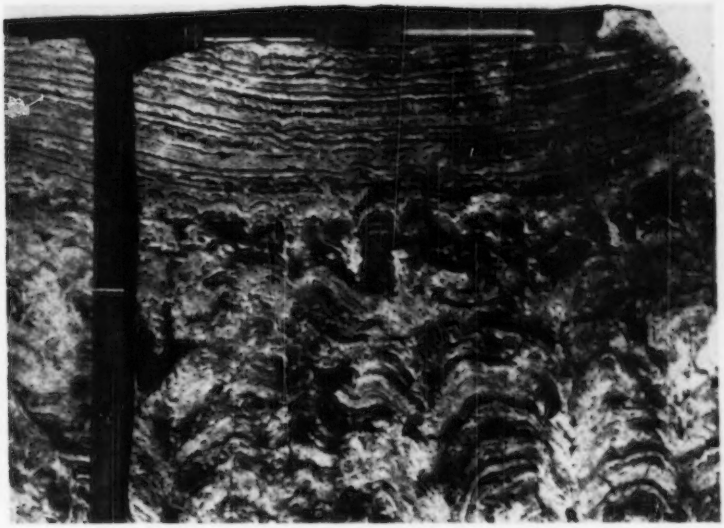


FIG. 1.

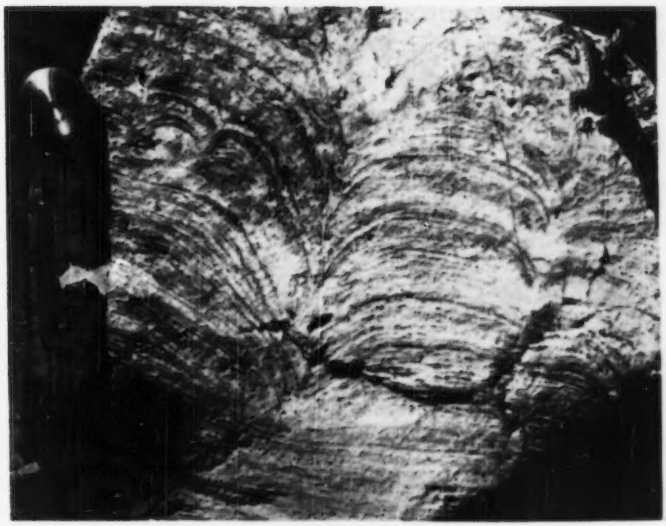


FIG. 2.

Note on Two Lineated Tectonites from Strathavon, Banffshire

By DONALD B. MCINTYRE (Grant Institute of Geology, Edinburgh University)

ABSTRACT

The principal tectonic terms employed are defined. A specimen of sheared quartzite from Corshellach is described. Shear-planes, drag-folds, and lineation are syngenetic. Their geometric relations show that the lineation is in *b*. Also described is a specimen of folded marble and graphite schist from Urlarmore. Elongated bodies of graphite schist represent tectonic thickening along the antiform hinges. Their maximum dimension, which is much greater than any other, is parallel to the lineation, but they have not suffered extension in this direction. The form of folds and rotated bodies shows that the lineation is again in *b*. The sense of the movement was towards the south-west. It is believed that throughout mid-Strathspey and Strathavon similar lineations bear the same relations to the kinematic directions.

I. NOMENCLATURE

TO avoid creating unnecessary difficulties by the use of ambiguous terminology the writer will use the following definitions :—

The *fabric* of any object is defined by the spatial arrangement of all the microscopic and macroscopic structural elements which it contains. A *deformation fabric* is one produced by the operation of stress.

Componental movements are those displacements and rotations which take place in a deformed body without destroying intergranular cohesion. A *tectonite* is a rock which has undergone componental movements.

An *s-surface* is any structural surface in a deformation fabric.

Lineation (*l*) is a nongenetic term for any kind of linear structure within or on a rock.

The *axis* of a fold, or of an *s*-surface, is the nearest approximation to the line which, moved parallel to itself, generates that surface.

The *profile* of a fold or of an *s*-surface, is the trace of that surface on a plane perpendicular to the axis.

The *a-axis* is the direction of movement. The *b-axis* is the axis of rotation. In most cases it coincides with the fold-axis, and it is usually perpendicular to the *a*-axis. The *c-axis* is normal to the *a–b* plane. The *a–b* plane is the movement plane or principal fabric plane. The *a–c* plane is usually a symmetry plane.

The definitions of *axis* and *profile* follow the usage of Wegmann (1929) and the alpine tectonicians (Lugeon, Argand). The remainder are based on those given by Fairbairn (1942) and E. Cloos (1946), and follow in broad lines the original usage of Sander.

II. Specimen of Sheared Quartzite from Corshellach, Glen Tervie

The Cromdale Hills separate the valley of the Spey from that of its tributary, the Avon. Composed of a group of metamorphosed quartzose sediments they lie between the typical Moine of the Central Highlands and the Dalradian of Banffshire. In 1896 L. W. Hinxman (p. 17) distinguished this group as the " Cromdale Hills Series ". In 1902 he included it in the Moine of the Central Highlands (p. 24).

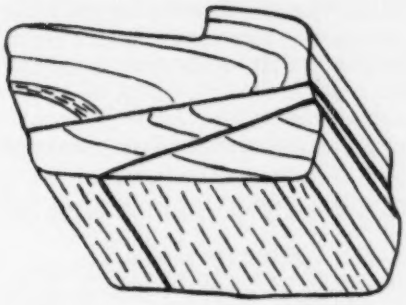
Linear structures were observed in these rocks at a very early date. Hinxman's map (one-inch, Sheet 75) published in 1895 has symbols indicating the direction *and sense* of " striping " or " lines of stretching ". " The rock," he wrote (1896, p. 19), " is thoroughly drawn out and often shows beautiful ' mullion-structure.' " This area has been studied in detail by the writer, and the results will be published in due course. Macroscopically there is a plane of symmetry perpendicular to the lineation : *a*-lineation has usually no such plane ; slickensides, for example, are smooth one way and rough the other. Hinxman did not state that asymmetry is present ; he simply affirmed that the lineation " shows " a north-westerly movement (i.e. parallel to the lineation). It seems that he must have assumed that the *a*-axis coincided with the lineation and that the sense of movement was up-dip. Present knowledge does not permit such assumptions to be made *a priori*.

Similar phenomena were found and recorded by Hinxman when he followed the Cromdale Hills Series towards the north (one-inch, Sheet 85). Where the quartzose members of the group have been sheared, " white mica is developed along the planes of movement ". At Corshellach (8 miles south-west of Dufftown), where the shearing is pronounced, " striping, produced by the drawing out of the mineral particles in one determinate direction, is often well seen, the direction of movement being to the north-west " (1902, p. 25).

The purpose of this section is to describe a specimen from Corshellach, and to demonstrate that its macroscopic fabric is not in accord with Hinxman's interpretation. Further data on the nature and significance of the lineation in mid-Strathspey will be given in a forthcoming publication. At Corshellach there is a small quarry, now largely overgrown. The floor is strewn with fragments of highly siliceous rock similar to that exposed *in situ*. The specimen described was found loose, and therefore its orientation is unfortunately unknown.

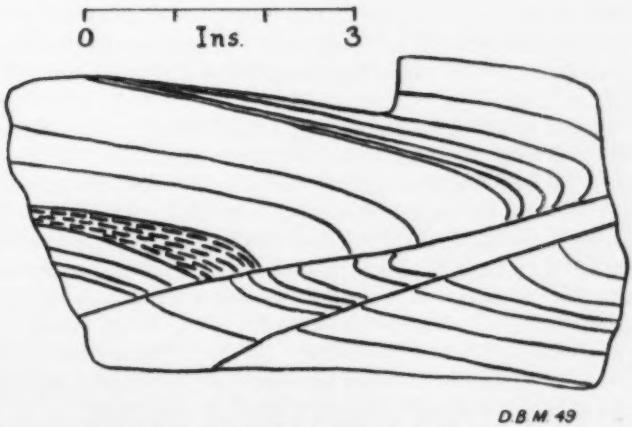
The specimen (Text-fig. 1) is bounded on two sides by *s*-planes (foliation). On one of these there is a well-developed linear arrangement of the crystals ; on the other no linear structure is apparent macroscopically. There is a plane of symmetry perpendicular to the lineation. Cutting obliquely across the specimen are two shear-planes,

but the rock is so thoroughly welded together that it shows no tendency to split parallel to these planes. The direction of lineation lies on both shear-planes ; if projected beyond the limits of the specimen, their



TEXT-FIG. 1.—Block-view of quartzite, Corshellach. Lineation is shown diagrammatically.

intersection would define this direction. Bedding is plainly visible on sections perpendicular to the foliation. If such sections are cut parallel to the lineation, a fine parallel ruling is seen ; the bedding and foliation are in the main sub-parallel. In sections cut perpendicular to the lineation, many of the bedding-planes are seen to change direction as they approach the shear-planes. Such a section is illustrated in Text-fig. 2. Close to the shear-planes the dip of the bedding increases and sometimes becomes inverted in the manner usually attributed to drag



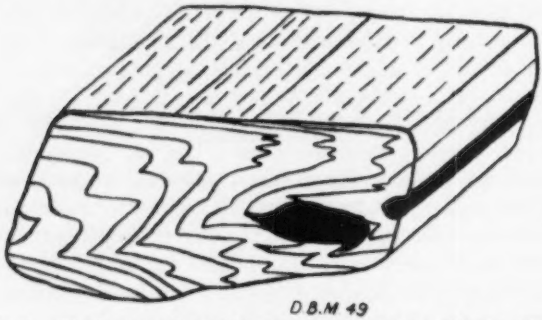
TEXT-FIG. 2.—Profile, perpendicular to lineation.

against a movement-plane. The axis of these drag-folds coincides with the lineation. Where the bedding and foliation are not parallel their intersection would likewise define the lineation-direction.

These geometric relations prove that the shear-planes, the drag-folds, and the lineation on this specimen are genetically related to one another. The direction of movement is clearly perpendicular to the lineation and not parallel to it, as Hinxman assumed. The " striping " is a *b*-lineation.

III. Specimen of Folded Marble and Graphite Schist from Bridge of Avon, Urlarmore

The specimen (Text-fig. 3) was found *in situ* in the River Avon,



Text-fig. 3.—Block-view of marble and graphite schist (black), Urlarmore. Lineation is shown diagrammatically.

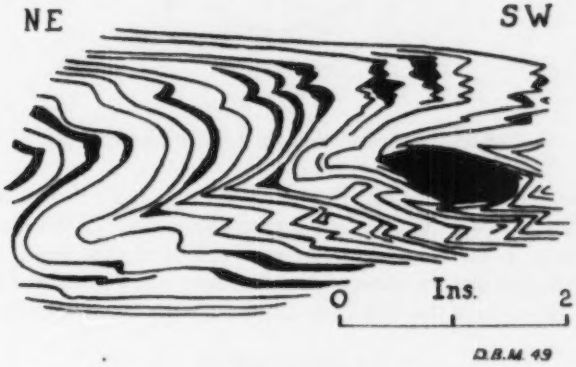
below the bridge at Urlarmore (1¼ miles N.N.W. of Tomintoul and 8½ miles S.S.W. of Corshellach). It consists of alternating marble and graphite schist belonging to the Banffshire Dalradian. The locality is little more than a mile from the outcrop of the Cromdale Hills Series (Moine).

The upper and lower surfaces are of graphite schist. They show the minute puckering which Hinxman carefully described in 1896 : " The original bedding-planes, as distinct from the foliation, are generally still recognisable in lines of different sedimentation ; while a third set of divisional-planes, arranged at a considerable angle with the foliation, can often be detected. These planes indicate strain-slip cleavage (*ausweichungsclivage*), and produce a minutely corrugated or puckered structure which is so constant a feature of these rocks, though less recognisable in the more slaty varieties " (p. 11). There is again a plane of symmetry perpendicular to the lineation. At this locality the latter plunges at 30° towards 120°–130° E. of N.

The rock is broken by joints which are nearly perpendicular to the

lineation. The surfaces so exposed show recumbent folds overturned towards the south-west (see Text-fig. 4). The fold-axes are very constant and are parallel to the lineation. Successive profiles show little change even though they are spaced at distances measuring many times the amplitude of the folds. Sections cut parallel to the lineation show parallel banding.

In the environment of regional metamorphism, marble and graphite schist flow readily. The profile (Text-fig. 4) shows that the graphite is concentrated along the hinges of the recumbent antiforms. This thickening of the graphitic layers has occasionally caused several of these to coalesce in one relatively large graphitic lenticle, of which an example is illustrated in Text-fig. 4. Such bodies have more or less

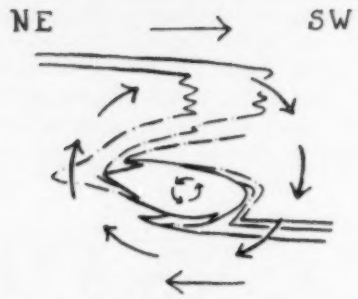


TEXT-FIG. 4.—Profile, perpendicular to lineation.

elliptical profiles and a considerable elongation parallel to the lineation. In the example described the maximum dimension is *at least* twenty times the minimum. At first glance these bodies could easily be erroneously interpreted as due to an *extension* parallel to the lineation. Indeed, Dr. E. M. Anderson, to whom the writer showed the specimen, was at first inclined to believe that in fact there had been such extension. There is, however, no evidence for extension in that direction. The thickening takes place in three-dimensions, and not in two; the maximum dimension of the body is necessarily parallel to the fold-axis, and this dimension *must* measure many times the length of the other two.

Of great significance is the orientation of the " feeders " of the elongated graphitic body. Looking south-east, in the direction of axial-plunge, these emerge in a clockwise direction, see Text-fig. 5. Relative to its environment, the body rotated in an anti-clockwise direction; the axis of rotation is parallel to the lineation and to the fold-axis,

i.e. the lineation is parallel to the *b*-axis. As it is unlikely that there was a source of energy within the body it is convenient to refer to a clockwise rotation of the environment and to conceive the body as playing a passive rôle. All movement is relative and as we live at the surface of the earth it is conventional to conceive the surface moving relative to the



TEXT-FIG. 5.—Part of Text-fig. 4, illustrating rotation.

interior, rather than the equally correct concept of referring all motion to a static exterior. Analysis of the macroscopic fabric of this specimen thus leads to the conclusion that the *a*-axis is at right-angles to the lineation, and that the sense of the movement was towards the south-west. The form of the folds (Text-fig. 4) supports this conclusion.

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Photo by S. Weatherall.

SLUMPED BRECCIA-CONGLOMERATE, BELLMAN QUARRY, CLITHEROE.

Some Features of the Lower Carboniferous Reef Limestones of Clitheroe, Lancashire

By Donald Parkinson

(PLATE XVI)

Abstract

The Clitheroe Limestone of Coplow, Salt Hill, and Bellman quarries is redescribed, particularly from the point of view of the origin and structure of the reef knolls and their relation to the surrounding deposits. Coplow knoll is considered to be the exposed part of a lenticular mass of upper C_1 reef limestone which originally sloped steeply east. An earth movement within the C_2 zone is marked by limestone breccias and a boulder bed, but there seems no evidence of pronounced erosion. A later uplift preceded the deposition of the Worston Shales. Slickensiding in the reef limestone is briefly discussed and possible effects of compaction of the sediments are considered. Three growth stages in reef formation are postulated.

1. Introduction

THE area of Carboniferous Limestone considered in the present paper forms a small part of the district described by the author in 1926. It lies in the north-east of Clitheroe and west of the tract of country stretching from Worston to Twiston which includes the largest reef knolls of the Clitheroe anticline (Parkinson, 1926, 1943).

During recent years the aspect of the Clitheroe quarries has changed greatly and features have been revealed which were not visible when the earlier work was carried out. It is the purpose of this paper to discuss these features and also others in the reef limestone which, though observed during the previous study, were not considered in detail.

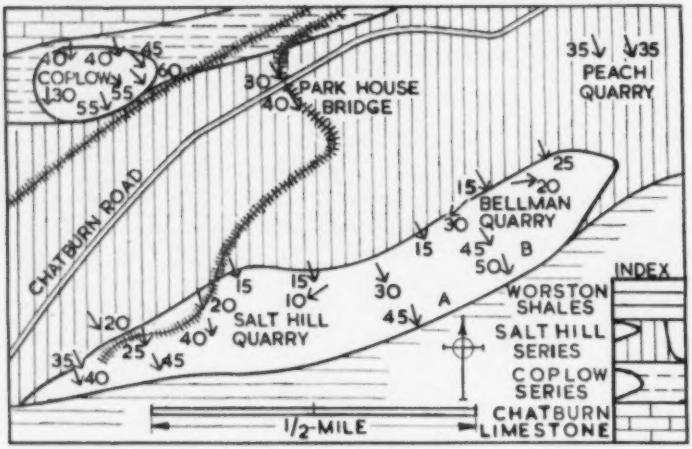
The non-calcareous residues of the Clitheroe limestone have been described by A. Bray (1939).

2. Stratigraphy

The reef limestones with their associated thin-bedded equivalents are upwards of 1,800 feet thick. Within the area covered by the map (Text-fig. 1) the non-reef deposits greatly predominate, but owing to the drift cover, exposures are few. The strata (Parkinson, 1926) were subdivided into the Coplow Series below and the Salt Hill–Worsaw Series above. Beneath the Coplow beds are the black Chatburn Limestone, the whole constituting the Clitheroe Limestone of Tiddeman (1875). The Worston Shales overlie the Clitheroe Limestone. The Coplow Series was originally assigned to the C zone and the Salt Hill Series to S. Later work (Parkinson, 1936) indicated that the Clitheroe Limestone terminates about the top of the C_2 zone. The boundary of C_1 and C_2 is uncertain, but is taken provisionally at the top of the Coplow Series which is considered to be of upper C_1 age.

3. Some Characteristics of the Reef Limestones

Coplow Quarry.—The words "Coplow Hill" appear on the Ordnance Survey maps and the writer remembers when the knoll was a prominent feature. Quarrying has not only removed the hill but has extended to well below the level of the surrounding low ground. The more or less complete dissection of the knoll has provided more data than were available a quarter of a century ago to enable a partial reconstruction to be made of the original reef. It should be noted, however, that strata formerly exposed at the south end of the quarry have been buried beneath tipped debris. Geologists will



Text-fig 1.—Geological Map of the North-Eastern End of Clitheroe.

regret that preparations are now being made to use this famous quarry as a water reservoir for the near-by Ribblesdale Cement Works. It is fortunate that a large collection of crinoids has been made from Coplow by Mr. James Wright, who has described many species in a series of papers in the *Geological Magazine*.

It was stated in the author's 1926 paper that the maximum thickness of reef limestone exceeded 400 feet. It is now thought that this estimate was high, 375 feet being considered a more probable figure. Owing to the absence of bedding in much of the rock, however, estimates of thickness can only be approximate. The maximum lateral extent of the knoll limestone is about 300 yards.

The reef limestone where characteristically developed is usually bluish-white ; it is occasionally tufaceous in small patches, is sometimes bedded and crinoidal, but is rarely brecciated. Its passage to

thin-bedded dark crinoidal limestone and shales takes place very rapidly. It can be seen on the top of the quarry on the west side, where soft black shales with thin intercalations of irregular and somewhat eroded discontinuous bands of limestone penetrate into the margin of the reef. At a few horizons within the quarry itself and grading into reef limestone are crinoidal calcareous muds which have yielded many species of crinoids and a few species of echinoids.

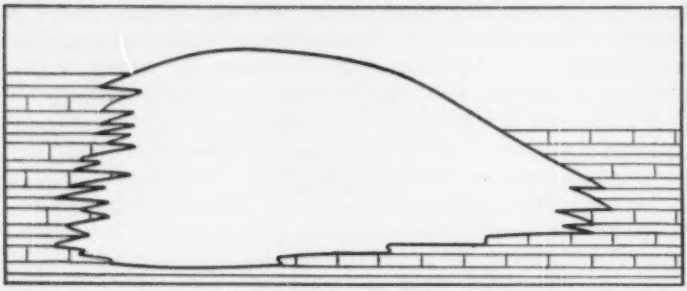
The basal layers of the quarry are dark crinoidal limestones with occasional thin crumbly black shales enclosing irregular lumps of limestone. From the north-west corner eastwards along the north face successively higher beds appear and in places the passage to reef limestone is seen, the change in facies being apparently accompanied by a thickening of individual beds. The transition takes place at progressively higher horizons towards the east and it is estimated that at the north-eastern extremity the base of the reef limestone is some 70 feet higher than at its lowest level near the north-western end of the quarry which presumably occupies a position near the line (or point) of elevation where the reef was initiated. The basal beds exhibit a succession of shallow folds with axes 10 to 20 feet apart trending roughly perpendicular to the regional strike. These undulations apparently do not extend upwards into the interior of the knoll. Their possible origin is referred to later.

Slickensiding is in evidence in various parts of the quarry. It is usually on a comparatively small scale, but quarrying has terminated on a length of 100 yards of the south-east side at an almost vertical slickensided face which runs approximately N.E.–S.W. The inclination of the striae is variable, but usually not many degrees from horizontal. Some fault breccia is associated with the movement, but in the writer's view there is no evidence of more than minor faulting. In the south-western corner of the quarry are subsidiary slickensided faces close to the main one and trending parallel to it, whilst a few feet of a vertically slickensided face also striking N.E.–S.W. are seen on the top of the west side of the quarry, but elsewhere slickensiding can be observed to trend in other directions.

The general dip of the beds is south to south-south-east and averages about 45°. On the south-east side it is 55–60° south-east, the strike changing rapidly near the north-eastern corner. The strike of the south-east face is about 35° different from the average strike of the north face, which approximates to the regional strike, and there is no indication that it is related to the slickensiding or to other effects of earth movement. The impression is gained that the beds of reef limestone converge towards the north-eastern corner of the quarry, or in other words that they are lenticular on this side of the knoll. It is therefore assumed that we have here an original slope of the reef.

If we further assume no complications due to earth movement, or to a possible steepening of the dip caused by compaction of the sediments we can calculate the original direction of this slope of the reef and the angle of inclination.

If the angle between the regional strike and the strike of the south-east face is denoted by β, the regional dip by α and the dip of the south-east face by γ it can be shown that if the whole reef is turned through an angle α parallel to the regional strike the angle between



TEXT-FIG. 2.—Sedimentation Diagram of the Coplow Reef, Clitheroe. Horizontal and Vertical Scale 1 in. = 310 feet.

the regional strike and original "strike" of the south-east slope is given by

$$\tan^{-1} \frac{\sin \beta \sin \gamma}{\sin \alpha \cos \gamma - \cos \alpha \cos \beta \sin \gamma}$$

and the original dip of that slope by

$$\cos^{-1} (\sin \alpha \cos \beta \sin \gamma + \cos \alpha \cos \gamma)$$

If α is assumed to be 40°, β 35°, and γ 55° the original direction of the south-east slope is shown to be approximately 73° to the present regional strike, which averages W.5° S.–E.5° N. at Coplow and to dip at an angle of 29½°.

This means that the south-eastern flank had an original trend N.12° E.–S. 12° W. and was a steep slope. From the bottom of that slope at the time when it began to be built up above the level of the non-reef sediments to the time when it attained its maximum growth the increase in thickness of the reef sediments towards the crown of the reef can be determined approximately from dip and strike considerations assuming no penecontemporaneous erosion of the deposits. This increase is estimated to be 225 feet. On the south-western side of Coplow exposures are lacking, but it appears unlikely that the reef rose very far above the level of the non-reef sediments to the west of it. The deeper water seems to have lain to the east.

The sedimentation diagram (Text-fig. 2), drawn to true horizontal

and vertical scale, illustrates a section through the reef in a direction perpendicular to that of the original eastern slope. The extent of the reef in a direction parallel to the eastern slope is indeterminable, but reasons are advanced later that it may not have been considerable.

Salt Hill and Bellman Quarries.—The reef limestone of Salt Hill has a maximum thickness of about 400 feet and extends laterally for a mile. The two large quarries have excavated almost the whole length and width of the knoll and there is thus a very considerable volume of reef limestone exposed. Not all the rock is fully characteristic of the reef facies and some of the basal beds of both quarries are bedded crinoidal limestones transitional between the underlying dark limestones and the obscurely bedded limestone of the knoll. Much of the reef material itself, however, is bedded crinoidal limestone and, in fact, is often composed of little else than crinoid debris. The thick deposit of this type of rock which caps the reef is well known and was commented on by Tiddeman (1875). It would indeed be little exaggeration to describe the whole mass as a crinoid reef, despite the occurrence of many species of brachiopods and numerous other forms.

Features characteristic of reef limestone which are much in evidence include unbedded and tufaceous limestone, brecciation, erosion surfaces, and a boulder bed. It has been suggested to the author that the bedding planes were obliterated during the movements that produced the intense slickensiding, a phenomenon which is particularly in evidence at the eastern end of Bellman quarry. The slickensided planes are usually vertical and although they strike in different directions the dominant trend varies between N.N.W.–S.S.E. and N.–S. As at Coplow, the movements are usually not far from horizontal and presumably quite small as there seems little evidence of more than minor displacement of the beds. Whilst agreeing that the slickensiding is indicative of some modification of the original configuration of the sediments the author would point out that unbedded limestones are a common feature of reef deposits which show no evidence of disturbance.

Sporadically distributed throughout the two quarries are irregular patches of calcite mudstone. In general, these inclusions are not true pebbles, but they are so numerous in places as to give the rock a brecciated appearance. The calcite mud may have resulted from precipitation in crevices which were sheltered from wave and current action. Locally, the calcite mudstone is bedded, but individual bands, which range from less than an inch to 2 or 3 inches thick, do not extend more than a few yards.

In the north-east corner of Salt Hill quarry the reef limestone is penetrated by irregularly bedded grey to black bituminous crinoidal

limestone, of which about 20 feet are exposed and within which is an erosion surface containing potholes a few inches in depth. Pronounced overstep of the underlying beds has not been proved and no more than a minor local uplift is indicated.

Evidence of a later uplift is of a different kind. At intervals along the strike of the south face of Bellman quarry are deposits of brecciated and conglomeratic limestone. The pebbles are usually small and irregular and easily removed from the matrix. Near the point marked A on the map (Text-fig. 1) the breccia-conglomerate is more or less continuous for a distance of 60 yards and displays some interesting features. Thin bands of calcite mudstone and shaly limestone, associated with eroded pebbles of reef limestone, exhibit minor contortions and other irregularities, the appearance (Plate 1) suggesting a certain degree of slumping.

About 80 yards from the south-east corner of Bellman quarry at the point B the conglomerate assumes the character of a boulder bed, the nature of which is not readily evident from a casual inspection. A close examination reveals a number of large irregular boulders of limestone interspersed with smaller ones, while occasional thin bands of "soapy" calcareous shales are seen to wrap round the boulders. A loose mass of rock measuring 8 feet by 5 feet by 4 feet which has become detached from this bed has an irregularly worn and pitted surface. Some of the larger boulders are not easily accessible; several of them seen in the lower part of the quarry face are slickensided. Occasional boulders of a similar nature have been observed at the same horizon elsewhere in the quarry.

These breccia-conglomerates are not more than 30 or 40 feet below the summit beds of the reef, the boundary of which with the overlying Worston Shales is nowhere exposed. They do not seem to have a well-defined base and their occurrence is sporadic, though apparently at a constant horizon. Similar deposits of the same or approximately the same age, but on a larger scale, have been described from the reef limestones of Thornley in the Bowland region (Parkinson, 1935).

4. The Non-Reef Sediments

These rocks are rarely exposed although they occupy a much greater area than the reef limestone into which they grade in the Worsaw Hill area to the east. In the mineral railway cutting immediately south-east of Park House Bridge are exposed about 50 feet of alternations of pale to dark crinoidal limestone and soft fissile crumbly shale. The lithology and fauna constitute a sub-facies common in the basin facies of the Clitheroe–Bowland region, but either rare or absent in the bedded rocks of the same age in the Dovedale area (Parkinson, 1949). The commonest genus in the shales is *Fenestella*, other forms including

zaphrentid corals, crinoids, and ill-preserved brachiopods and gasteropods. Crinoid heads are not uncommon in the limestone bands, but good specimens are rare.

The rocks of Peach quarry are rather higher in the succession than those in the cutting and consist of dark impure mostly highly crinoidal irregularly bedded limestone with shaly intercalations and chert bands and lenticles. About 175 feet of beds are exposed. The commonest fossil is *Productus* (*Plicatifera*) *humerosus*. Otherwise fossils, apart from crinoid heads and occasional zaphrentids, including *Fasciculophyllum densum*, are rare. The fossils are poorly preserved.

Immediately north of the western end of Salt Hill quarry is a small disused quarry with a few exposures of crinoidal limestone, whilst a few feet of impure croinoidal limestone are exposed in the tramway cutting just north of Bellman quarry and immediately below the base of the reef limestone.

5. Earth Movements

Following the deposition of the Chatburn Limestone in which the reef facies is completely absent, events took place which provided the conditions for reef formation. One important factor influencing the changed type of sedimentation was almost certainly elevation of the sea-floor, and it is thought probable that the uplift was accompanied by minor undulations, the crests of which provided the sites on which the reefs were initiated. The elevation was a temporary phase and throughout the period of reef sedimentation the area was probably, with minor fluxuations, a sinking one. Towards the close of this period an uplift of some significance is suggested by the breccia-conglomerates and boulder bed of Bellman quarry, but it is difficult to find proof of actual unconformity. Hudson and Dunnington (1944) have suggested on faunal evidence that in the Clitheroe area the major effect of the mid-Dinantian movement is to be found below the upper limestone of Salt Hill or at about the level of the breccia beds. The writer has been unable to discover a faunal change at the horizon of the breccia, unless the local occurrence of corals in the upper limestone is to be regarded as constituting a faunal change. The brachiopod assemblage found in the crinoidal limestone is similar to that in the reef limestone below the breccia. Whether or not the horizon of the breccia corresponds in position with the mid-Dinantian unconformity elsewhere, the break within the Salt Hill limestone has not been shown to be a major one and in the author's view is of less significance than that occurring at the top of the limestone. Although at Salt Hill itself the thick crinoid bed at the summit of the reef limestone suffers no appreciable overstep by the Worston Shales for at least a mile, there is some evidence in the areas both at the east and south-west that

these shales lie with some discordance on the underlying beds (Parkinson, 1943).

6. Possible Effects of Compaction

The compaction of muddy sediments has been studied by O. T. Jones (1944) who made brief reference to the influence of compaction in the dips of the Worston Shales near the Worsaw knolls (p. 151). He pointed out that these shales, which are overlain by a great thickness of Upper Carboniferous deposits, "must have undergone a high degree of compaction, whereas the knolls which they surround are relatively incompressible. In the shales immediately surrounding the knolls dips of 20° to 30° may, therefore, be expected from compaction alone." In a few places where the Worston Shales overlie and are exposed in the vicinity of the knolls they do, in fact, present dips higher than the regional dip. On the low ground between the knolls where the shales rest on non-reef limestones they dip normally, and in the lower beds at angles less than the average regional dip (Parkinson, 1943, pl. xix). Unfortunately, there are no exposures in these shales near the east side of Worsaw Hill and elsewhere close to the larger knolls where, owing to compaction, they may be expected to display quaquaversal dips away from the reefs on which they overlap.

Professor Jones further suggests that the thickening of non-reef sediments towards a reef recorded by Dixon (1921, p. 131) is probably due to diminishing compaction as the amount of compressible material in the layers decreases. Such thickening, as previously mentioned, is seen where the bedded rocks approach the reef on the north side of Coplow and the effect here may well have resulted from the greater compressibility of the thin-bedded sediments. But the thickening continues to well within the core of the reef itself where the sediments, if compressible at all, would suffer the same degree of compaction. It is considered, therefore, that the thickening within the knoll itself results from the mode of accumulation of the sediments.

The three regions of a reef distinguished by O. T. Jones, (1) a relatively incompressible core, (2) a fringing area of "fore-reef" detrital material, and (3) a surrounding region of non-reef facies, are all present at Coplow, though (3) is not exposed. Along the western side of the knoll the fore-reef deposits in general have the regional dip and almost the regional strike, the dip of the partly detrital material being usually less than that of the reef limestone. Compaction of the thin-bedded sediments between the wedges of reef limestone may have increased the dip of the latter in the manner indicated by O. T. Jones, but owing to inadequate exposures the evidence is not conclusive.

The shallow folds immediately below the base of the reef limestone of Coplow quarry have been referred to and it is now suggested that

they are a consequence of compaction. These undulations, as was noted in the author's 1926 paper, tend to be more calcareous on the crests than in the troughs. The rapid alternations of calcareous and muddy sediments in the same layers might be sufficient under high pressure to cause the observed effects.

Finally, it should be evident that the main effects of compaction at Coplow would be expected in the non-reef sediments immediately east and west of the knoll. Although these beds are not exposed near the reef limestone they can be presumed to be alternations of thin bedded limestones and shales and in consequence are likely to show abnormal dips.

7. The Origin of the Slickensiding

Although the planes of slickensiding vary in direction they can be roughly separated into two groups which trend approximately in the directions of the present regional dip and strike. At Salt Hill the dominant trend is N.–S. to N.N.W.–S.S.E. ; at Coplow it is N.E.–S.W. to E.N.E.–W.S.W.

It seems at least possible that the N.–S. displacements arose during the Variscan earth movements which gave rise to the Clitheroe anticline when the reef limestones were buried beneath a great thickness of sediments. These sediments in the vicinity of the buried reefs of Coplow and Salt Hill contained a considerable proportion of shaly material and would yield to pressure much more readily than the massive reef limestone. There would tend to be some differential movement between the two types of deposit, together with small accommodation movements within the more resistant reef limestone which might explain the slickensiding. The actual extent of the movements need not have been more than a few feet, or possibly even less than a foot, but they apparently operated along planes in some cases of hundreds of feet in length.

The N.E.–S.W. slickensides probably had a different origin, and it is suggested that the cause may have been hydrostatic pressure. During the period of compaction of the surrounding sediments the hard relatively incompressible mass of the Coplow reef would be subjected to severe strains which might have found relief in minor displacements along planes of weakness such as bedding planes. At both Coplow and Salt Hill, but particularly at Coplow, occasional bedding planes exhibit slickensiding. The large slickensided face on the south-east side of Coplow is roughly parallel to the strike, but inclined at an angle of about 20° to the bedding planes in its vicinity.

8. Notes on Reef Structure and Growth Stages

Coplow is (or was) the largest of a line of knolls of upper C_1 age stretching E.N.E. from Brungerley Bridge, Clitheroe, to beyond

Twiston, a distance of five miles. Most of these structures are quite small and some are apparently not many yards in lateral extent. Since they all project from an outcrop dipping S.S.E. at relatively high angles they presumably represent cross sections of reefs buried towards the south and eroded to the north and they may, therefore, originally have been elongated in some direction very different from the present regional strike. It has been suggested above that the south-east slope of Coplow knoll is part of the original eastern margin of a reef that trended east of north to west of south, and the inference is that the other (smaller) reefs of the same age might have had a similar trend. The exposed parts of most of them, however, are so small that it seems unlikely that they could originally have been more than local accumulations.

As regards Coplow itself, the fact that towards the north the lower beds of the reef can be seen to pass into a non-reef facies suggests that the reef may never have extended far in that direction, though this is not conclusive since evidence is lacking of such a facies change in the middle and higher portions of the reef. Towards the south some of the upper layers tend to become shaly which may or may not be significant as indicating an approach towards the southern limit of the reef. On the whole the evidence is consistent with the view that the reef was originally lenticular with the longer horizontal axis lying at an angle of 70–75° to the present strike and with a cross section containing the shorter horizontal and vertical axes represented by Text-fig. 2.

East of the area covered by the map there are a few small knolls overlying the line of Coplow knolls and equivalent in age to the lower part of Worsaw. These structures also are probably local accumulations, but the larger knolls of the Worston–Twiston region, including Worsaw, with a thickness of 1,400 feet, may originally have extended considerable distances in a direction perpendicular to the present regional strike (Parkinson, 1943).

Salt Hill remains to be considered, but little has been deduced regarding its original disposition and extent. This knoll is a mile wide and contains a maximum thickness of 400 feet. On the north face of Salt Hill quarry the knoll limestone changes locally to a black crinoidal limestone which may indicate an approach to the northern margin of the original reef or it may merely mean that this part of the reef was affected by muddy currents. On the south side the reef limestone may run some distance underground.

At this stage a few words should be said on the question of reef-builders. Here the author prefers to reserve judgment, since in large part the knoll limestone is substantially unfossiliferous. It has been remarked that Salt Hill can be regarded as a crinoid reef. Crinoids,

in fact, are dominant, not only in the Clitheroe knolls but also in the contemporaneous non-reef deposits where, interbedded with muddy sediments, they form bands indistinguishable from some of the crinoidal limestone in the knolls. This suggests that they are not essential reef-builders, a view which is supported by the fact that the structurally similar reefs of the Dovedale area are much less crinoidal. In the Clitheroe knolls brachiopods, though represented by a wealth of species, are relatively rare when their remains are considered as a fraction of the total sediment, while corals, molluscs, and bryozoans are negligible in bulk. Bryozoa, in fact, seem to be more abundant in the non-reef than in the reef facies. Microscopic organisms, to judge from the limited number of thin sections of reef limestone examined, are comparatively scarce but a final conclusion awaits the results of further work. On the available evidence there were either no essential reef-builders or their remains have not been preserved in quantity. Whether their structure was dependent upon any particular types of organisms or not the reefs were certainly inhabited by a great variety of creatures of which comparatively few individuals have been preserved as fossils.

Detailed examination of the two knolls of Worsaw (Parkinson, 1943) and Coplow has, in the author's view, given quantitative expression to some of the original views of Tiddeman, which it should be remembered, though now shown to be not applicable to the Cracoe knolls (Bond, 1949) were based also on the knolls of the Clitheroe–Bowland region. The argument in the following paragraphs attempts to expand Tiddeman's thesis and leads to the suggestion of three growth stages, though it does not imply that all these stages will be present in individual cases. In the first stage growth is both outwards and upwards, but usually more rapid outwards ; in the second stage it is mainly upwards, and in the third stage upwards and inwards.

To enable the reef to grow at all the conditions of depth of water, temperature, and food supply would have to be favourable. In the Clitheroe region suitable conditions for reef formation did not appear during the deposition of the Chatburn Limestone, which is a uniform deposit. This formation was apparently terminated by a general shallowing of the sea, though an actual break in the sequence has not been proved. Locally, on the crests of shallow folds which may have been anticlines, monoclines, or domes, the reef-like structures came into being.

In considering the history of an individual reef let us assume in the first place that it is initiated on the summit of a shallow dome which at low tide stands a little below sea-level, and let us assume further that the sea-floor remains at the same elevation. Under such conditions the reef could not grow appreciably upwards. It might grow in all

directions outwards or possibly in one direction according to such factors as availability of oxygen or food supply, but it would probably not extend far since normal sedimentation surrounding it might soon restrict its growth. Under the same conditions of no elevation or subsidence a reef initiated on an anticlinal crest would suffer a similar fate except that, mathematically speaking, it would begin its existence as a line rather than a point.

On a rising sea-bottom the reef could only grow laterally and soon the centre portion would appear above sea-level and denudation might begin. The inference is, therefore, that the most likely conditions for prolonged growth are those of a sinking area. On the whole it would seem that growth could begin during or immediately following a period of elevation, but that it could only continue during subsidence.

In basins such as that of the Clitheroe–Craven region the periods of elevation were brief compared with those of subsidence and it is reasonable to suppose that the reefs in general came into existence during the short periods of minor uplift. This would account for the first stage of growth being more outwards than upwards (Text-fig. 2). When the sea-floor began to sink the growth would tend to be upwards (Stage 2) and so long as subsidence was not too rapid the sediments outside the reef could accumulate at the same or nearly the same rate as those of the reef and there would tend to be a fore-reef margin consisting of tongues of non-reef sediment projecting into the reef. If the rate of sinking increased beyond a critical value either the reef would cease to grow or stage 3 would be initiated. The reef would grow upwards at a quicker rate than that of the surrounding sediments ; it would tend to thicken out towards the crown, and the difference between the depth of water at the crown and the bottom of the slope would continue to increase. Sedimentation would continue, probably at a diminishing rate, outside the reef, but the nature of the margin would change and the non-reef material instead of projecting into the reef and passing laterally into reef limestone would begin to overlap on to its consolidated surface, and near the margin would be expected to incorporate fragments from it.

As growth continued the angle of inclination of the reef slope would increase. If the reef were merely a shell bank the limit might be reached at the angle of rest of the sediments, but if it were a true reef there seems no reason why the angle of slope should be limited. In the case of Worsaw it may have been as high as 50° in places (Parkinson, 1944). The reef would become narrower as the sea-bed sank. Tiddeman's view that it would grow up as a cone is probably the true one in some cases ; in others, and in particular the larger structures, the form would be that of a ridge, either symmetric or asymmetric. Reef building would probably cease on the slopes when

the water exceeded a certain depth and as suggested by Tiddeman (1892) would finally cease when the top of the reef became " too narrow to give an area of animal growth or until the rate of sinking was too great for the animals to keep pace with it and the water consequently became too deep to support such forms under conditions favourable to life ". Rejuvenation of the reef could obviously be caused by temporary halts in the subsidence.

A regional uplift might, of course, prematurely terminate the process of reef building, and this seems to have happened in the case of the upper (C_2) line of knolls in the Clitheroe region. But no evidence has been noted of such an uplift at the top of the Coplow Series and the Coplow reef itself may well have ceased growing while the region was still sinking.

There is evidence in the Clitheroe and Slaidburn anticlines that some of the reefs had a steeper eastern than western flank which suggests a downwarping on the east side during sedimentation. The facts at Coplow (Text-fig. 2) suggest that during the later period of reef formation the sea-bed sank more rapidly on the east than on the west side, but owing to lack of exposures in the south-western part of the knoll the reconstruction of that portion is somewhat problematical. The three largest of the C_2 knolls, namely Worsaw, Twiston (Parkinson, 1944), and Long Knotts, in Little Bowland (Parkinson, 1935), have steep dip slopes on the east side and these reefs are considered to have had steeper slopes on that side than on the west suggesting accumulation contemporaneously with the developments of gentle monoclinal flexures with axes running north–south.

9. The Succession Within the Reef Limestones

In a comparison between the sequences of the Clitheroe and Swinden anticlines Hudson and Dunnington (1944, p. 207) comment that " there is no published account of the details of the succession within the Clitheroe reef limestones and until such details, both faunal and lithological, are known, any correlation with other areas can only be a general one ". While agreeing wholeheartedly with the latter part of the statement the author would express the opinion that his own rough subdivision into three faunas, Coplow, C_1 ; lower Worsaw, lower C_2 ; and upper Worsaw (Salt Hill), upper C_2, is as detailed as can be expected on present knowledge of the faunas. Any further subdivisions would probably have no more than local significance and, in fact, at Worsaw itself, where the wholé of C_2 consists of reef limestone, most of the rock is so poorly fossiliferous that the prospect of obtaining a detailed faunal succession is small. Furthermore, the brachiopods, on which any succession in knoll limestone must depend,

evolved very slowly, and most of them persist with little change through considerable thickness of strata.

The difficulty of correlation of the Dinantian zones of different areas is evidenced by the continually changing views on the ages of different members of the Clitheroe Limestone. Thus, in 1944 Hudson and Dunnington placed the base of upper C_2 as high as the crinoidal limestone at the top of Salt Hill limestone and continued C_1 into the Worston Shales ; but more recently Hudson (1949) has referred the top of the Salt Hill limestone to the top of C_2 and the Worston Shales to S_1–S_2. The latter view is in line with the author's correlation of 1936.

The author is indebted to Mr. Stanley Westhead, of Clitheroe, for his company and help in the field on many occasions and for the photograph of the breccia–conglomerate in Bellman quarry. He also wishes to thank Mr. D. J. Billson, Manager of Ribblesdale Cement, Ltd., for his kindness in providing him with a plan of Coplow Quarry. The mathematical expressions on page 340 were derived by the author's colleague Mr. C. H. Leigh-Dugmore.

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Rejuvenation in a Rhabdosome of *Dictyonema flabelliforme*

By O. M. B. Bulman

(PLATE XVII)

Abstract

An abnormal specimen of *Dictyonema flabelliforme* showing close-set bifurcation of the branches in a portion of the distal mesh is described and figured, and possible interpretations are considered.

THE subject of this note is a remarkable specimen of *Dictyonema flabelliforme* from the Transition Beds of the Shineton Shales in Cherme's Dingle (in the Wrekin District of Shropshire), collected by the Sedgwick Club on an excursion in 1948.

The rhabdosome has a length of 7½ cm.; by development with a needle the sicula was exposed, but distally the mesh is somewhat damaged and displaced, so that no reliable figure can be given for maximum breadth. At about 5 cm. from the sicula the breadth (compressed) is some 4·7 cm., giving a length/breadth ratio only slightly more than 1 : 1. This, together with the density of the stipes (7–8 in 10 mm.) and dissepiments (4–5 in 10 mm.) suggests that the form is close to var. *anglica*, though its large size would be more readily associated with *forma typica*. Thecae number 14–16 in 10 mm.

For more than 5 cm. from the sicula the rhabdosome shows a regular mesh, with well-marked zones of branching at approximately 1½, 6, 13, 22, and 35 mm. As will be seen from the illustration (Pl. XVII) these zones are not mathematically regular and the figures cited are not rigidly exact, but a fairly reliable average can easily be obtained; and it is clear that the positioning of such zones will be largely responsible for the shape of the rhabdosome and its length/breadth ratio. In other words, though they have not been stressed in past descriptions, it is probable that such zones will prove a convenient way of expressing a feature of systematic importance, not only among the varieties of *Dictyonema flabelliforme* but also in its dendroid and anisograptid descendants. The chief obstacle to their use is the slight uncertainty as to position of a given specimen (which might cause different observers to record slightly different values) and the need for complete and well-preserved rhabdosomes.

The main interest of the specimen in question lies in the branching at the distal end. Laterally, the mesh is torn and the branches displaced, but they appear to have been normal and almost undivided. Centrally, however, all the stipes seem to have terminated at a uniform level 5½ cm. from the sicula, beyond which certain of them (every second or third) continue with the branching characters of a youthful rhabdosome as set out above. Whereas in the normal rhabdosome branching would

here be too infrequent and sporadic for the recognition of any "zones" whatever (as, indeed, appears to be the case laterally), here in this rejuvenated portion recognizable zones of branching occur at 1½, 5, and 11 mm. intervals, which compare reasonably well with those of the proximal end.

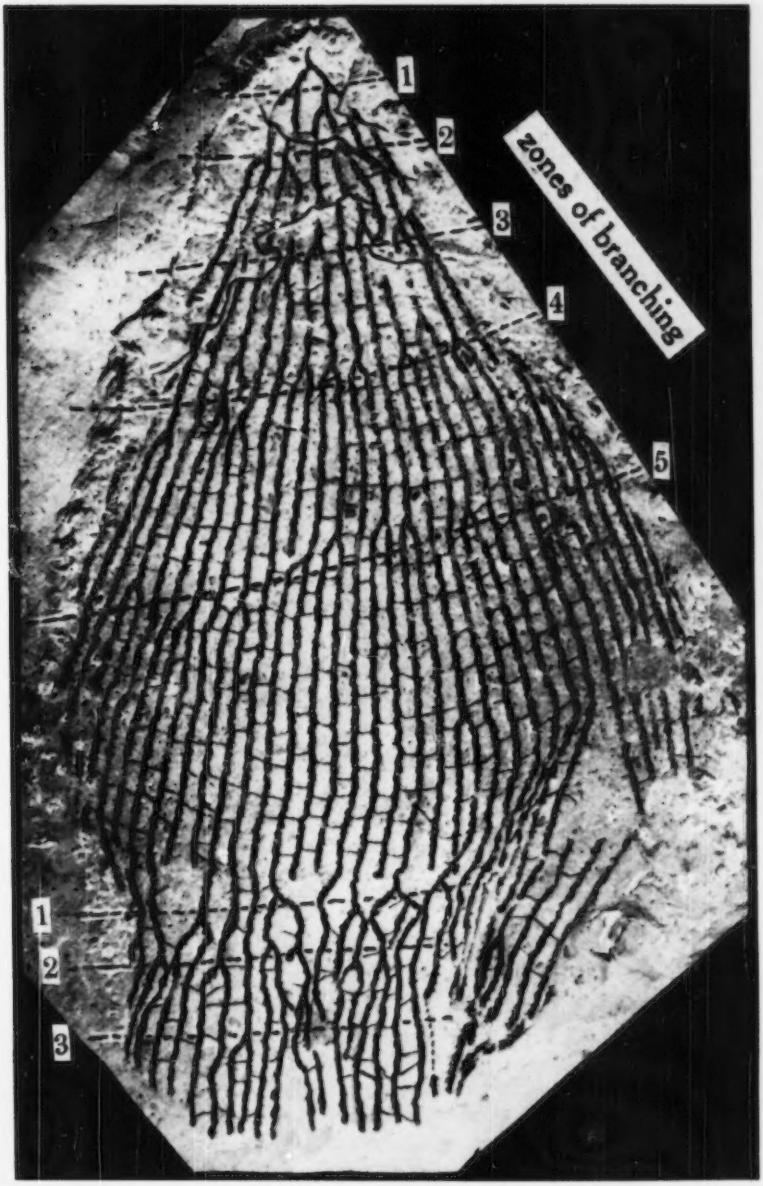
One explanation might be that we are concerned here with regeneration in the repair of an injury; but the uniform level at which the majority of the branches of the "normal" rhabdosome terminate (5½ cm. from the sicula) over a breadth of nearly 2½ cm. makes this somewhat improbable.

More likely it represents rejuvenation unassociated with regeneration. The post-mortem distortion and displacement of the lateral part of the rhabdosome makes it difficult to assert positively that the lateral portion was perfectly normal. If it was, then the rejuvenation must have been limited to a portion of the distal circumference, flanked by uninterrupted normal growth.

The most probable interpretation would seem to be that there was an appreciable pause at the 5½ cm. length stage, which would in any event represent a large rhabdosome for var. *anglica*. As a result of some unknown stimulus, this was followed by an abnormal phase of renewed growth (itself a form of rejuvenation). Where (as apparently laterally in this specimen) most branches were able to respond, the normal mesh continued almost uninterruptedly; but where (as centrally) only a small number of the branches could for some reason respond, rapid bifurcation was necessary to maintain the peripheral diameter of the rhabdosome. This compelled simulation of the juvenile, proximal, characters of branching. It seems probable to the writer that even so, some significance attaches to the approximate correspondence in spacing of the zones of branching if, as he believes, they are the expression of a specific character.

EXPLANATION OF PLATE

Dictyonema flabelliforme cf. var. *anglica*. Shineton Shales (Transition Beds), Loc. α 26, Cherme's Dingle, near the Wrekin, Shropshire; Sedg. Mus., A23397. × 2. Specimen showing normal zones of branching (1–5) at the proximal end, and rejuvenation zones (1–3) distally.


1
2
3
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zones of branching
1
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3

Speculations upon the Outline and the Mode of Disruption of Gondwanaland

By LESTER KING

(*University of Natal, Durban, South Africa*)

ABSTRACT

Certain small discrepancies in Du Toit's (1937) reconstruction of Gondwanaland are discussed and suggestions made as to its mode of disruption.

THE idea of an immense southern continent in past geologic time took shape in Blanford's famous Presidential Address to the Geological Society of London in 1889, and was accepted by Suess in order to explain the truly remarkable correspondences in the late Palaeozoic and Mesozoic geology of regions now widely sundered as India, Australia, South Africa, South America, and Antarctica. But difficulties inherent in visualizing so huge a landmass, and the contrary tenets held by adherents of the theory of Permanence of Continents and Ocean Basins, led to other attempts to connect these areas by means of hypothetical land-bridges and isthmian links (Schuchert, 1932, Willis, 1932) many of which were fantastic. Neither concept seemed wholly satisfactory.

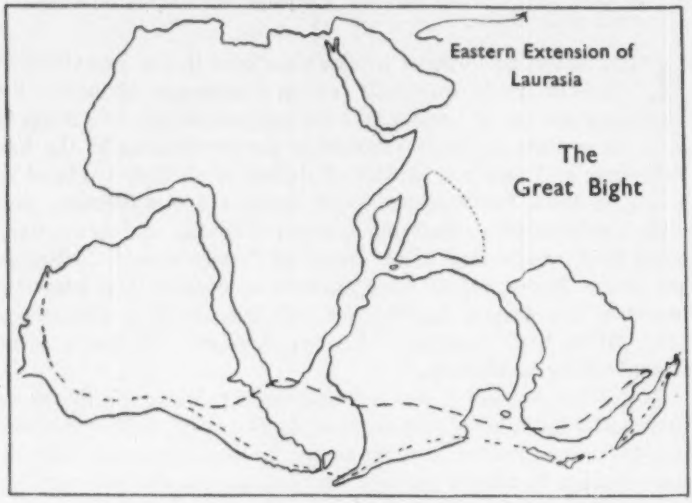
Out of this impasse a way was discovered ; Wegener's theory of Continental Drift, in the able hands of du Toit (1928, 1937) was found to solve the contradictions of the earlier theories, though not without some damage to current geological prejudices. An able summing up of the problem at this stage was given by Holland (1937) in an address " The Permanence of Oceanic Basins and Continental Masses ".

Du Toit's summary, and reconstruction of Gondwana (1937), is a neat and workmanlike job appealing especially to those dwelling in *Gondwana moderna* who were also confronted with the problems he set out to solve. We accept it gratefully ; but with the passing of a decade sundry small discrepancies have appeared, and newer data and viewpoints require to be stated. A number of these are here discussed.

(1) The position of Antarctica in du Toit's reconstruction has seemed to require revision, and before his lamented death I was able to make the following suggestion to him. Antarctica, it seemed to me, should be brought more towards South Africa and rotated slightly (Text-fig. 1), thus somewhat shortening and straightening both the Palaeozoic Samfrau geosyncline and the belt of Tertiary folding.

Moreover, whalers who have visited Seal Bay, in Crown Princess Martha Land, had described to me a range of Black Rock Mountains in the coastal hinterland which they estimated to be possibly 5,000 feet

high. Now ranges of black rock are less common than might be believed, and an analogy was immediately suggested between these and the frowning black rock precipices of the Drakensberg, which on the reconstruction here submitted lies apposed to Crown Princess Martha Land. If the present Scandinavian-British Expedition to Queen Maud Land reaches this spot the matter can be easily tested, for if the black rocks of the Antarctic range do correspond with the



TEXT-FIG. 1.—Readjusted assembly of Gondwanaland.

— — — Ancient mountain ranges of the Samfrau geosyncline.

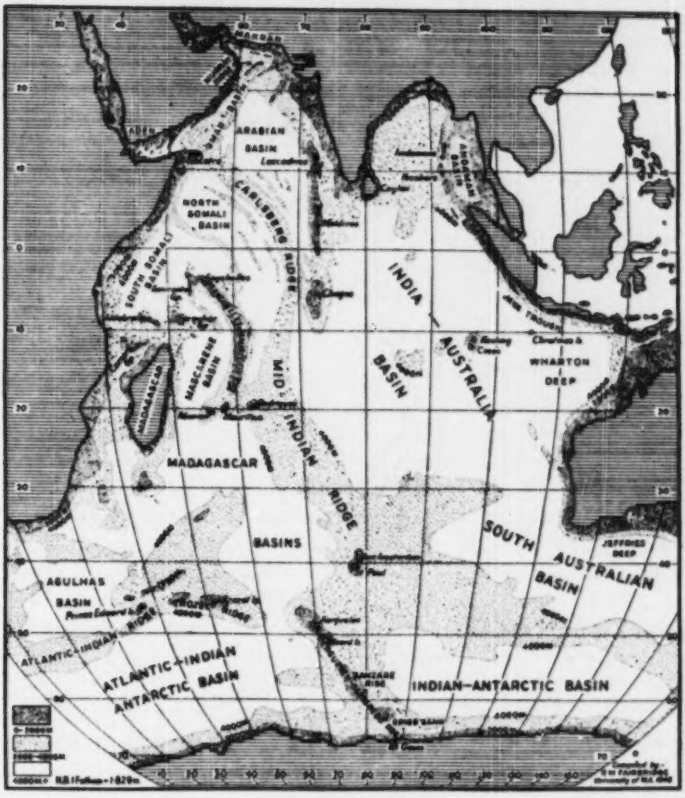
– – – – Approximate position of late Mesozoic and Tertiary fold belt.

Drakensberg basalts then they must be underlain by inferior members of the Karroo sequence.

From the records of Shackleton's voyage in the *Endurance* down the eastern side of the Weddell Sea it is plain that the plateau type of geological structure continues beneath the continental ice sheet through Coats Land down to latitude 73° S., where, in startling contrast, appear two mighty *valley* glaciers, the Allan Macdonald and Dawson Lambton. Here surely is a change in the subglacial terrain from broad plateaux to a landscape of great valleys and ridges. What can these be but the folded ranges of the Samfrau geosyncline, collinear with the folded mountain ranges of the southern Cape Province ?

(2) Our fittings of these pieces of the Gondwana jigsaw in this manner has left upon the opposite side of Antarctica (and Australia)

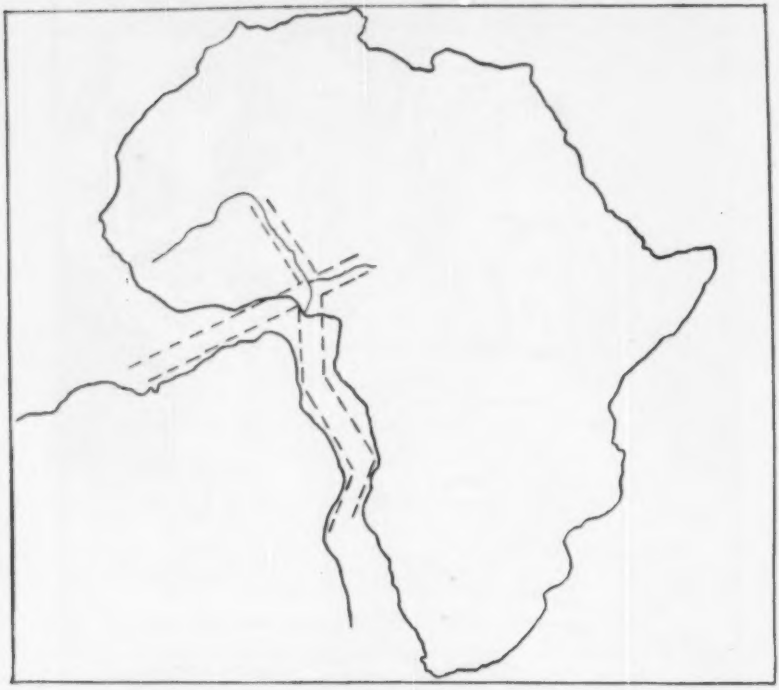
a gap to which attention must now be directed. The position of Madagascar seems fixed upon du Toit's reconstruction by the whorl of strike lines appropriate with those of the adjacent East African



TEXT-FIG. 2.—The Floor of the Indian Ocean (after Fairbridge).

coast. The position of Peninsular India is surely no more adjustable : it must fit in the appropriate wedge (Text-fig. 1) between Antarctica and Madagascar—on what is known of the geology of Enderby Land, assuredly no inappropriate placing. We are then faced inevitably with a huge bight between Western Australia and Arabia. This bight must have been part of a wide open sea stretching across to the south-eastern promontory of Laurasia (Thailand and Borneo) which reached far beyond Gondwana on the east. The " sialic vacuum " between the two super-continents in this region is at first disconcerting.

But this very " vacuum " receives startling confirmation from the structure of the Indian Ocean basin. As Fairbridge has so clearly brought out (1948) the basin of the Indian Ocean is divided from north to south (Text-fig. 2) by the " mid-Indian Ridge ". The western segment contains several islands the rocks of which are continental in



TEXT-FIG. 3.—The extension of the Atlantic Rifts into Africa as the Cretaceous rift valleys of Nigeria.

type (e.g. Seychelles) together with several conspicuously arcuate submarine ridges. There is a " sialic flavour " about it. Between India and Australia, however, the ocean bottom is distinctly deeper, with few submarine inequalities, and the volcanic Keeling Cocos as the only islands. This bears the stamp of primary ocean of Pacific type, invaded on the north-east, like the true Pacific, by the folded mountain chains and island-arcs of Burma and the East Indies.

Any reconstruction of Gondwana must therefore inevitably leave an area corresponding to the Indian–Australian oceanic basin as a part of the original, circumferential, proto-Pacific Ocean ; and our

readjustment of du Toit's Gondwana, begun in the south, leaves just such a bight in the north as is required by the curious double nature of the basin of the Indian Ocean.

(3) The fitting of " the bulge of South America into the Gulf of Guinea " by both Wegener and du Toit has consequences which should further confirm the original juxtaposition of these masses. When an initial rift formed between the two continents that rift had a right-angled bend about the " bulge " of Cape San Roque. Such right-angled bends in rift systems are distinctly rare, and we might expect instead that two lines of rift had developed intersecting one another. If this is so, then it is reasonable to look for extensions of these rifts into Africa where they would continue independently (Text-fig. 3).

Both the Niger and Benue rivers flow in valleys sunk far below the plateaux on either side, and both are floored with Cretaceous rocks. That of the Benue is the older ; it contains marine Lower Cretaceous rocks that were folded and eroded before terrestrial Upper Cretaceous rocks were laid upon them : that of the Niger contains only the Upper Cretaceous series. Despite marked uplift of Africa during the Tertiary era, these beds are still only at moderate elevations above sea-level, showing either that they were of great depth during the Cretaceous or that they have independently failed to rise during the Tertiary. The ancient scarps of the original Cretaceous rifts have either been obliterated under subsequent erosion or, surviving as scarps, have retreated far from their original situations. It is not impossible that some of the superb scarps which delimit the plateau areas far away from the present valleys originated as the Cretaceous rift scarps.

(4) The Lebombo rhyolites, andesites, and tuffs of South-East Africa, reaching in a straight line north–south for over 300 miles from Southern Rhodesia to Zululand, were specially studied by du Toit (1929) who, noting that they followed upon the Stormberg basalts of plateau type, proved also that they were erupted *pari passu* with the monoclinal warping of the coast, itself clearly due to the dismembering of Gondwanaland. In places the acid volcanics are succeeded by further basalts.

The magnitude of the phenomena is tremendous—the total thickness of volcanics in the Lebombo exceeds 30,000 feet, while the length of outcrop is 300 miles and may well be twice as much if the formations are continued southward on the monocline off the coast of Natal and Pondoland. Here is something possibly unique ; where did the huge mass of acid material (some 25,000 feet) come from in a region where plateau basalts were also abundantly poured out ? The rocks, though termed rhyolites, differ materially in appearance from the rhyolites of typical volcanic regions such as New Zealand, and many are andesitic in composition and texture. I can only conclude that

the acid lavas and tuffs are remelted sialic material and that the lavas of intermediate composition are probably hybrid. Here, along South-east Africa, a powerful monocline forming the margin of the continent has clearly carried down an enormous bulk of Archean basement and Karroo rocks of the kind exposed in the coastal regions to-day. At the same time, thinning of the sialic crust by stretching had permitted the upsurge of wholly unusual quantities of plateau basalt with superabundant heat and volatiles. As a result, the previously-existing rocks were melted and made their way back to the surface along profound tensional fissures as the rhyolites of the Lebombo.

Granitization of a crumpled sialic root forced down under compression is a familiar theme nowadays, but here is the opposite : mobilization following stretching and thinning of the crust under tension and upsurge of sub-crustal material (the basalt) from below.

One question remains, why are not equivalent lavas to be found on the ruptured edges of other continents. These, it seems, moved away from the zone of remelting, Africa remained almost in place. The absence of a corresponding Lebombo on the west may be ascribed either to a slight eastward movement of the continent at the time of Gondwana disruption, or to the fact that the necessary deep tensional fissures did not develop. But related rocks are not absent : above the Karroo basalts of the Kaokoveld in South-West Africa is a set of porphyries that may well have had a congruent history.

(5) The Cretaceous glaciation in Australia has been something of a puzzle, for it does not appear to have analogues in other continents. But under drift it may receive simple explanation. In the passage upon a great circle course from its position in Gondwana to its present position Australia would move into a more southerly latitude and may well have endured a transient refrigeration.

(6) In 1944 I offered an explanation for one of the most baffling biogeographic phenomena, the origin of the New Zealand marine mollusca, which may now be offered to a wider public. At first, in the Triassic and Jurassic, the New Zealand molluscan faunas were of Tethyan and Pacific affinities, and were clearly marginal to the great Gondwana continent (Text-fig. 1).

Before the Cenomanian, New Guinea, Western Australia, and New Zealand had received new faunas, the same as at Trichinopoly, in Peninsular India. What had happened ? Gondwanaland (Text-fig. 1) was in process of disruption and the new faunas migrated first to the Cape and then to New Zealand along the open rifts about Antarctica. India, then moving north, impinged upon Laurasia, and closed the Tethyan mediterranean. The southern fauna did not mix with the Tethyan, though only a few tens of miles separate the two in Bengal and Assam.

Lastly, in the late Cretaceous, came the greatest mystery of all. New Zealand received an influx of Patagonian (*sic*) mollusca, the last invasion that it has so received. From the migrant stocks of that date the modern marine mollusca are directly descended. How can the palaeobiologist explain this influx?

On the hypothesis of continental drift it is to be anticipated. Consider the movements of the lands. In the later Cretaceous the new Atlantic and Indian Oceans had met round the southern horn of Africa. Antarctica, moving south, acquired a population of littoral mollusca from Patagonia (see Text-fig. 1), which, as opportunity offered, migrated along the " northern " shoreline far to the east, so far that the remaining distance to New Zealand could be covered by normal means of dispersal. The connection was then, as Antarctica moved out still further, broken for ever. On no other combination can the curious distribution of these three assemblages of Mesozoic mollusca be so deftly explained.

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Axes of Active Warping in the New Zealand Seismic Region

By C. A. Cotton (Victoria University College, Wellington)

Abstract

Geomorphic evidence is described of very recent upwarping of the shore of Hawke Bay north of Napier, and, as this is of local extent, the suggestion is made that here and in adjoining coastal districts folding is, or recently has been, in progress, with this and another upheaved rib farther to the north-east as anticlinal axes. The coastally drowned areas of Poverty Bay and the north-east and south-west corners of Hawke Bay have escaped the upheaval, and it is suggested that they occupy negative, or synclinal, axes of a fold pattern.

Recorded data are insufficient to show to what extent, if at all, the axes of transverse upheaval recognized in the coastal districts extend westward across the main geanticline of the island. All or most of the axial ranges in this belt have recently been rising, however, for this is indicated by the presence of terraces in the valleys of outflowing rivers and by the fact that the vertical intervals between terraces increase upstream.

The Hawke Bay Shoreline

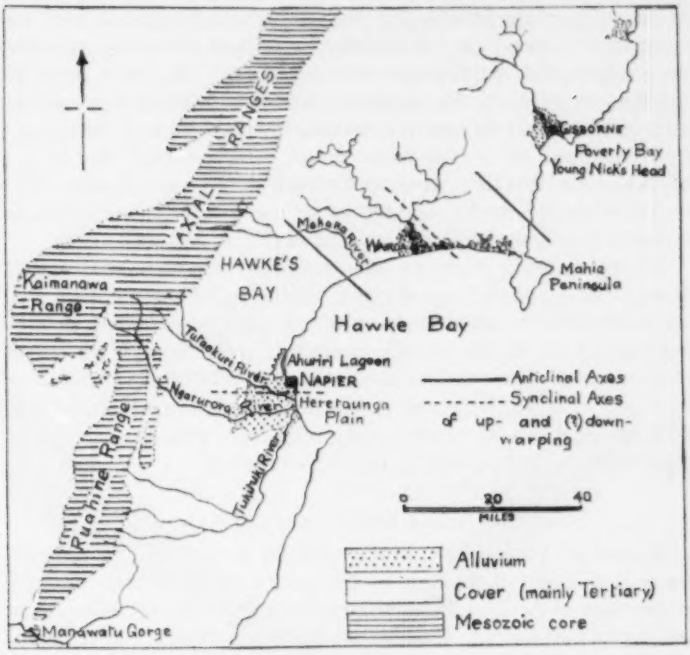
THE theory has long been abandoned that the peculiar-shaped Hawke Bay re-entrant of the east coast of the North Island of New Zealand (Text-fig. 1) is a sunkland bounded by a curved fault ; but an echo of this old theory is to be found in a recent work by Schaffer (1948) who, apparently unaware of the conclusions reached by New Zealand investigators, has attributed the origin of the Napier earthquake of 1931 to movement on such a fault, or *Kesselbruch*.

As a matter of fact, the origin of this great bay is unknown, but its initial outline must have been very different from that of the present shoreline, and it is very improbable that it was a curved fault bounding an area of gravitational subsidence. It is just as likely that the re-entrant was downfolded as that it was downfaulted. The bay as a whole is rather ancient, as is indicated by the full development of a submarine shelf along this part of the coast and by the maturely smoothed, almost semicircular outline of the bay, which has been assumed despite the varied nature and history of different parts of the shoreline composing it, for the details of form in these testify to the occurrence of strongly differential vertical movements since the bay has been in existence. The smoothly curved outline of the major embayment is of submature to mature development in the current shoreline cycle, and no part of the coast closely resembles a fault scarp.

Diversity of Movement

At each end of the bay are rectified (submature) shorelines of submergence, and the middle portion, which presents a continuous

line of cliffs towards the sea, has been maturely developed by strong marine retrogradation, though features of the land indicate that recently there has been great upheaval. In very recent times it is clear that there have been diverse movements, here upward and there (probably) downward. It is tempting to regard these movements as the expression of folding along axes extending inland (Text-fig. 1);



TEXT-FIG. 1.—Locality map of part of the east coast of the North Island of New Zealand. Approximate positions of fold axes assumed to account for warping are shown.

but, on the other hand, future investigation may show that downward and upward movements have not been contemporaneous. Neither may it be assumed that movement in any particular area has gone on continuously, or has been repeated always, in the same sense; for the latest upheaval, that of 1931 (Marshall, 1933), raised part of the coast (from Napier northward) which had previously been embayed, possibly in part by downwarping, though it is difficult to separate the effects of such local movement from those of the post-glacial eustatic rise of ocean level. It is possible that an earlier, though still rather recent,

upheaval of much greater amplitude, of which there is evidence in the middle portion of the coast of the bay, has also raised a shoreline previously drowned. This is by no means obvious, but it is possible that evidence of such a condition has been destroyed by excessively vigorous marine erosion during and after the latest movement (upward). Whether the movements were simultaneous or not, there is evidence of very considerable downwarping (relative, at least) on certain axes in the Hawke Bay and Poverty Bay region and of upwarping on others; and these may be at least tentatively regarded as synclines and anticlines of a fold pattern. The study made by Henderson (1933) of the movement which took place at Napier in 1931 indicates that the region is in compression. The fault, interpreted by Henderson as a high-angle thrust, which caused the Napier earthquake of that date, developed apparently on a new fracture line; and possibly it is to be regarded as an accident, or minor break, in a region undergoing deformation dominantly by folding.[1]

Allowance being made for glacio-eustatic drowning, the contrast between drowned and non-drowned parts of this coast is such that the latter must be very strongly upheaved, whether the former have or have not been simultaneously depressed. Features of the actual shoreline and of the coastal strip behind it indicate the presence of two axes of strong upheaval (tentatively anticlinal axes, Text-fig. 1) separated and flanked by three belts which have been either depressed or have lagged behind during a general upheaval.

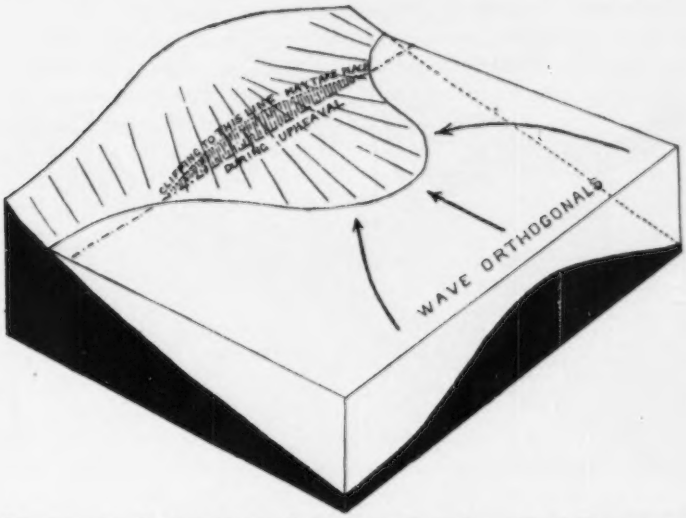
Poverty Bay and Wairoa Lowlands

Centred on Poverty Bay, in the northern part of the area affected, there is a broad downwarp of the land surface causing extensive embayment of the shoreline, which has been followed by much alluvial infilling in that district. Summit profiles of the dissected land surface inland from this Poverty Bay basin slope down towards its axis, especially from the south-west; for between the Poverty Bay basin and that of Wairoa, in the Hawke's Bay district, there is a strongly uparched area. Here a deeply dissected rib of high country runs out, with altitudes of 2,000 feet and more, though consisting throughout of soft Tertiary strata, to the bold coast between Young Nick's Head and the Mahia Peninsula.

South of this high rib, however, the upland surface descends to the north shore of Hawke Bay, which is deeply embayed by valley drowning, though the mouths of the bays thus formed are bridged by bars, and the lagoons enclosed by these have been filled with

[1] Studies made by Imamura (1939) have led him to discredit the "block theory" of the structure of Japan and to interpret active earth movement in parts of that region in terms of warping rather than faulting.

alluvium. This is either a synclinally warped belt or one which has at least escaped the upheaval that has affected ribs of land to north-east and south-west of it. It extends to and includes the fertile Wairoa valley, which opens into the northern part of Hawke Bay and consists of extensive valley plains flanked by low ridges and spurs of subdued form. Near the sea in this area there are no river terraces or other traces of recent rejuvenation. The hypothesis that the Wairoa basin is a persistently negative area subject to actual downwarping receives some support from the fact that downward earth movement to the extent of more than a foot took place here in 1931, as was shown by railway relevelling after the Napier earthquake of that year (Henderson, 1933, pl. x). South-west of the Wairoa valley, however, the new



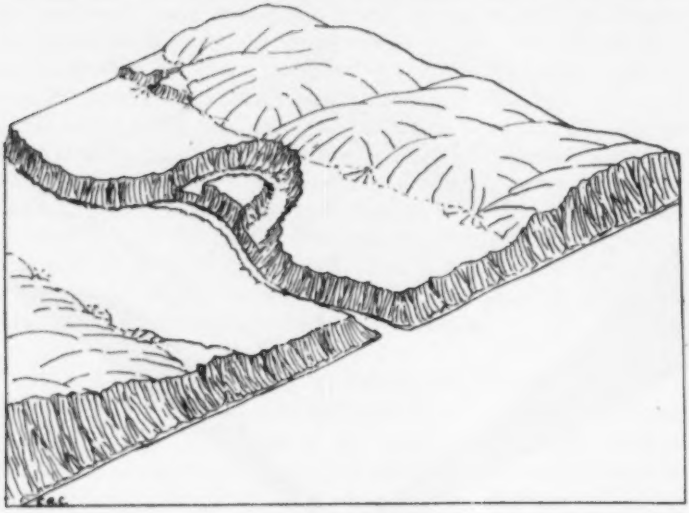
TEXT-FIG. 2.—Concentration of wave energy and marine erosion on an anticline with seaward pitch emerging transverse to the coast.

levels indicate uplift at this time to the extent of about 2 feet ; while north-eastward of the negative belt there was little or no change of altitude.

MOHAKA COASTAL CLIFFS

South-westward the Wairoa basin is flanked by another upheaved rib of country. The boundary here is not so abrupt as to suggest the presence of a fault scarp, but there is instead an appearance of progressively greater upheaval south-westward, the valleys becoming

deeper and more sharply cut, with progressively higher terraces bordering them. At the mouth of the Mohaka River the coast is strongly cliffed by marine erosion. One would expect to find here an extensive coastal salient in sympathy with positive movement of the land, unless perhaps the rising mass was cut off seaward by a fault which was progressively rejuvenated; but there is no collateral evidence to support such a hypothesis. The hypothetical coastal salient arrived at by deduction would consist of recently emerged sea-floor, i.e. a local development of young coastal plain, the outline of which would define the nose of the newly formed anticline (with presumably seaward pitch). The absence of such a salient in this case



TEXT-FIG. 3.—Generalized view of the mouth of the Mohaka River.

can be explained only by assuming that coastal erosion has been extremely vigorous during and since the uprise of the land. During anticlinal upheaval of the submarine coastal shelf in the form of a pitching anticline the convex form assumed by the sea-floor would automatically cause convergence of wave orthogonals (Text-fig. 2) and concentration of the activity of marine erosion on the emerging area. (Compare Shepard, 1948, p. 41.)

The marine processes having been sufficiently active here to pare back the nose of a presumably seaward-pitching anticline as it emerged, any new coastal plain locally fringing this coast at its infantile stage has already been removed by marine erosion, so that the lower

valley and bordering terraces of the Mohaka River are sliced off as with a knife, and the terraces end abruptly over coastal cliffs (Text-fig. 3).

The Mohaka valley is sharply and strongly rejuvenated (Text-fig. 4), quite obviously as a result of extremely recent upheaval, unless, as seems very improbable, the whole rejuvenation is to be attributed to an enormously rapid retrogradation by marine erosion, which must have affected only a portion of the coast. The river is a powerful one, filling the inner valley with a flowing stream (not a tidal estuary) and is capable of rapid and vigorous lateral corrasion. Yet the incised meandering trench in which it flows is still as narrow as the river itself, and its side walls are nearly vertical right to the mouth, though this valley is excavated in a very soft, almost incoherent mudstone. A former valley plain that has been widely developed by lateral river corrasion remains as extensive terraces on each side of the river at a height of 300 feet, and there are also higher terraces, which indicate earlier upheaval. The Napier-Gisborne railway, keeping to the main terrace, crosses the river on a bridge 300 feet high.

TEXT-FIG. 4.—View looking up the Mohaka River and valley, showing the main terrace at 300 feet above the river and another higher terrace.

South-westward of this point the highway and railway are forced inland by engineering difficulties due to coastal cliffing and a rejuvenation of the valleys of small streams which has been produced in part by upheaval and in part by coastal retrogradation of this high rib of country. Leaving the Mohaka valley they pass over the uparched surface of a peneplain (Fig. 4, distance) dissected to a shallow depth by open, fully mature valleys of small streams which for the most part have not yet experienced rejuvenation as an effect of the upheaval

which has caused the deep incision of the more powerful Mohaka River. South-west of the Mohaka the coastal cliffs attain heights up to 1,300 feet, where they intersect the highest parts of the uparched surface. Farther south the easily eroded mudstone terrain in which the valley of the Mohaka is cut is followed by a younger series consisting mainly of a 500 ft. thick formation of resistant shell limestone.[1] The attitude of this is nearly horizontal, and its surface forms a high structural plateau more or less at the peneplain level; but below this surface some rivers are incised in escarpment-walled gorges.

The Heretaunga Plain

As Napier (at the south-west end of Hawke Bay) is approached the altitude of the plateau or peneplain remnants decreases, though the terrain consists still of the same limestone. This descent is the southern flank of the upheaved rib, or anticlinal belt. It continues towards the depression in which the Heretaunga Plain lies, occupying a great coastal embayment now filled with deep alluvium. Here it is obvious that the initial outline of the shore has been intricate, and it still remains so within the bar-enclosed bay forming the Ahuriri Lagoon. The shoreline has been completely rectified, however, by the building of bay bars, and this has been followed by extensive alluviation. The unstable Tutaekuri, Ngaruroro, and Tukituki rivers are still engaged in filling in what remains of the original embayment. The landscape of the coastal belt is here without terraces or other traces of river rejuvenation. The hills, though composed of the same limestone in which farther north gorges disect a high plateau, are of subdued, mature form, testifying if not to tectonic depression at least to absence of upheaval such as has affected the upwarped belts or ribs earlier described. These are indications either that this area is in the axis of a persistent "low" or that any valley features due to earlier rejuvenation have been sufficiently lowered to be submerged and buried.

In spite of strong present-day seismicity and the actual intersection of the land surface by earthquake scarplets, including that which emerged in 1931 (Henderson, 1933), the landscape around Napier, consisting of plains and pleasant rolling hills with an old-world look, presents a specious appearance of stability; but this can only be because of its remoteness from structural "highs", or axes of active anticlines. Farther to the south-west, indeed, in the southern part of Hawke's Bay province and the adjoining part of Wellington, terraces

[1] The 16 mile to an inch Geological Map (1948) does not differentiate between these two contrasting terrains, both being of Pliocene age, and fails here, therefore, to give any helpful indication of structure for geomorphic or geographical purposes.

and rejuvenation of rivers—notably of the upper course of the Manawatu River—mark another belt in which upheaval has recently been, and probably still is, in progress.

The Question of Transverse Anticlines

Recognition of actively positive ribs in the coastal districts raises the question of whether the fold structure here developing merely frills the margin of the main geanticline of the North Island, which trends north-east and has the Mesozoic greywacke formations of the axial ranges of the island as its core. It is possible that axes of active transverse anticlinal upheaval extend across the main geanticline. The latter is rising, at least in parts, as is shown by the evidence of repeated rejuvenation of the rivers draining its flanks. In general, the terraces which border these streams diverge headward in a manner indicating considerable upheaval in their headwaters (Oliver, 1948). The details of the geomorphology of the region have been insufficiently studied, however, to show to what extent the rate of the arching recently in progress has varied from place to place along the geanticlinal axis, or to define the positions of axes of transverse anticlines, if such there be.

As regards the position and structure of occasionally emergent parts of the axial belt arising as embryos of ranges of the modern orogen in early times, nothing is definitely known of pre-Pliocene palaeogeography. In the latter part of the Pliocene period, however, when the New Zealand geanticline was beginning to assume its present form, the continuity of the embryonic main range was broken for all time by straits at places where marine strata are found transgressive on to and even across the axis of the island. One of these lies west of Napier, where a fossil peneplain of early Pliocene development is still partly covered by thin Pliocene limestone on the Kaimanawa Range (at 4,000 feet altitude) and on the north end of the Ruahine Range (at 3,000 feet) and is now being exhumed as well preserved plateaux of considerable extent (Speight, 1908; Waghorn, 1927). Sixty miles south of this also, where the axial range is much narrower, there is another similar sag in its crestline, which comes down here to 2,000 feet altitude in a saddle veneered with marine Pliocene strata. It is at this point that the Manawatu River breaks through the greywacke core entrenched in a superposed gorge, which is also antecedent to the latest horst-like uprise of the mountain belt (Adkin, 1930).

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Some Large Felspar Augen from near Ilorin Town, Nigeria

By Basil C. King

(PLATE XVIII)

Abstract

Large augen, composed principally of single crystals of potash felspar, are sporadically distributed in certain banded gneisses. It is inferred from structural and textural evidence that the augen have formed by metasomatic processes.

THE augen described occur in banded gneisses from a locality near the main road about one mile south of Ilorin.

The banded gneisses consist essentially of alternating flat and parallel bands of medium-grained leucocratic and melanocratic material, characterized respectively by an abundance of quartz and oligoclase (with subordinate potash felspar) and of biotite and hornblende. Individual bands are thin (a few millimetres at most) and are impersistent when examined in detail, but show complete textural continuity one with another.

Frequently the rock shows broader, impersistent, but conformable leucocratic bands or lenses up to as much as a centimetre in width which, where lenticular, correspondingly disturb the contiguous dark folia. They resemble the normal thin leucocratic layers in displaying textural continuity with adjacent folia, but also contain occasional larger crystals (up to 3 or 4 mm.) of both quartz and felspar (oligoclase and potash felspar).

The augen are sporadically distributed throughout certain of the banded gneisses and vary in size from small blebs to prominent objects as much as 6 or 7 cm. in length (Pl. XVIII, A and B). The augen are invariably composite structures, each of which is formed of a well-defined crystal of glassy-looking microcline, partly or completely surrounded by leucocratic material of medium grain in no way distinguishable from that forming the broader leucocratic bands and lenses and sometimes actually continuous with the latter. The leucocratic material is concentrated at the corners of the " eyes " and may be quite absent from the flanks of the structures.

A conspicuous feature is the sweeping aside of the gneissic banding by the felspar augen. If, however, attention is confined to the melanocratic layers it is evident that the degree of peripheral curvature diminishes rapidly away from the augen and at a distance of a few centimetres the layers are once more uniformly flat. The local disturbance has, in fact, been accommodated by " closer packing " of the dark bands, with corresponding diminution in width, or even suppression, of leucocratic layers.

In some instances a melanocratic layer may be traced in a continuous sigmoidal curve from the corner of an " eye " to its outer edge. More usually, however, the innermost layers are not deflected in this way, but terminate more or less indefinitely as they are followed into the auge ; only the layers that lie somewhat farther from the corner of the " eye " being characteristically deflected around its periphery. In this manner relic portions of melanocratic layers are commonly found in the leucocratic material at the corners of augen, although they are sometimes represented only by a number of mafic " clots " with little or no parallelism.

Mafic clots are also found within the microcline crystals, but only in sparing amount and rarely in distinct lines. Under the microscope other enclosures of typical gneiss mosaic, often retaining the orientation seen outside the augen, are commonly observed in the microcline (Pl. XVIII, C and D). Replacement relations are always displayed towards the gneiss mosaic, not only by the large microcline crystals, but also by the sporadic larger crystals of quartz and felspar in the leucocratic material. A characteristic feature is the development of blebs of myrmekite in crystals of oligoclase where these are partly or completely enclosed by microcline (cf. Sederholm, 1916, p. 131 ; G. H. Anderson, 1934, p. 189 ; and King and de Swardt, 1949, p. 37).

The terms " augen " or " augen structure " are purely descriptive and, judging from the numerous accounts of augen-bearing rocks, it is certain that more than one mode of origin is possible. Thus, felspar augen in the Lewisian gneiss have been regarded as relics of phenocrysts that have escaped crushing (cf. Harker, 1932, pp. 167, 300). Where the augen form " nodes " between opposing undulations of sinuous shear planes such a mode of origin would appear to be indicated (cf. Peach, Horne, etc., 1907, pp. 199–200).

In the Ilorin occurrence both macroscopic and microscopic evidence show that the augen have developed within an earlier fabric and that their formation has not been attended by any visible signs of general deformation, sharp dislocations, or crushing. Read attributes the development of augen in Sutherland to injected pegmatitic material (1931, pp. 106, 108) or more generally as related to " injection-metamorphism " or " injection processes " (p. 116), but the isolation of the individual augen in the Ilorin occurrence is incompatible with their having been formed by a process of mechanical injection of felspathic or quartzo-felspathic material. The observations are, indeed, only consistent with their formation by metasomatic processes. The local displacements, evidently attributable to the growth of the large microcline crystals, are compensated within very short distances, so that it is questionable whether the formation of the augen has occasioned a volume increase in the rock as a whole.

A particularly clear demonstration of the development of augen by metasomatism has been provided by Oulianoff (1932), for the augen described occur in schists that are manifestly of sedimentary origin. Large felspar porphyroblasts (including augen) are commonly found in regions undergoing granitization (cf. Anderson and Hammerand, 1940 ; Backlund, 1936 ; and Wegmann, 1938, pp. 44–6, 108). A petrographic affinity with pegmatization rather than with the larger scale process of granitization is, however, often apparent. Thus, many of the structural and textural features displayed by the Ilorin augen are analogous to those seen in certain pegmatites of the near-by Osi area, where leucocratic bands in the gneisses assume a " knotted " appearance with the development of large felspar porphyroblasts during pegmatization (King and de Swardt, 1949, pp. 24–6).

It is inferred that the Ilorin augen were formed as composite metasomatic structures by the segregation into bands and lenses of the constituents of near-by leucocratic layers in the original banded gneiss, together with the exaggerated development of sporadic crystals of potash felspar in some of these segregations. As in the case of more widespread pegmatization only the introduction of potash is necessarily implied.

Attention may also be directed to the close analogy between the composite augen and the orbicular or ovoid structures that are found in such granites as Rapakivi (cf. Backlund, 1938, pp. 366 et seq.). Backlund argues for the development of the ovoids by metasomatism, a conclusion that is supported by the occurrence of similar structures in the invaded rocks (cf. also Wegmann, 1938, pp. 109–111).

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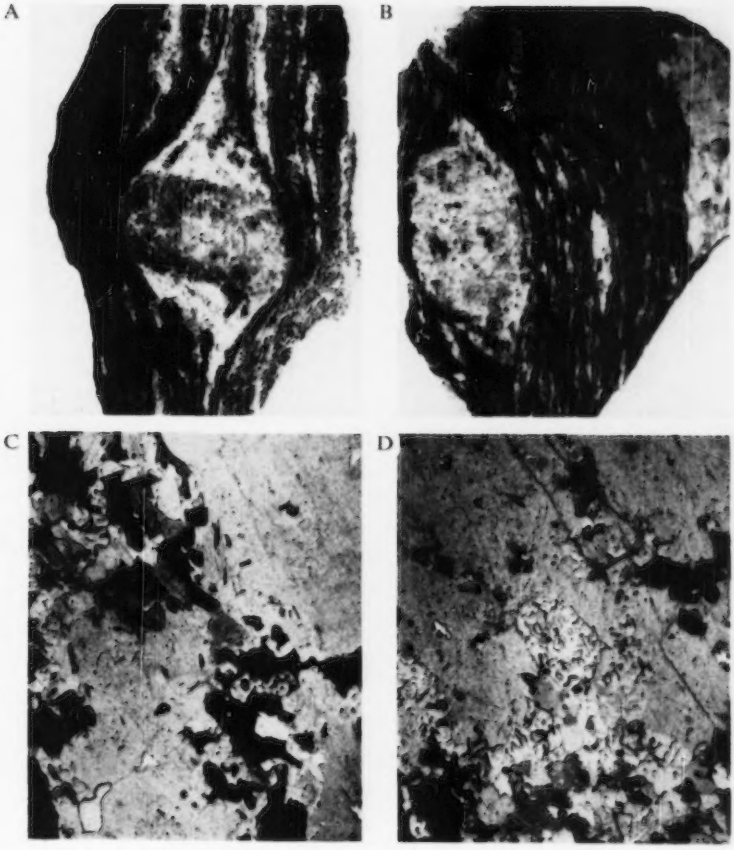
EXPLANATION OF PLATE

A and B.—Polished specimens of felspar augen in banded gneiss. (Width of large augen about 1½ inches.)

C.—Part of a large crystal of potash felspar forming an auge, illustrating the enclosure of minerals and aggregates representing relics of gneiss mosaic.

D.—Margin of large potash felspar showing the extensive development of myrmekite in the adjacent mosaic and as inclusions.

(Microphotographs : nicols crossed ; magnification 20 diameters.)


A
B
C
D

The First National Geological Survey

By V. A. Eyles (H.M. Geological Survey) [1]

Abstract

In France a National Geological Survey was planned in 1822 by the Corps Royal des Mines, a government institution, in association with its subsidiary, the Ecole des Mines. The first objective was a rapid Survey of the whole of France, with the intention of preparing a general Geological Map of the country, to be followed by a more detailed Survey, based on the Départements. Field work for the general map commenced in 1825, and was completed in 1835; and a Geological Map of the whole of France, on a scale of approximately 8 miles to the inch was published by the Ministry of Public Works in 1841. The project was carried out entirely under the direction of the Ministry, at public expense. As a National Survey it thus preceded that of Great Britain, established in 1835, by some ten years.

GEOLOGICAL Surveys are, to-day, accepted as a normal and necessary part of governmental activity, and exist in almost all countries in the world. This was not so 150 years ago, and it was only during the early years of the nineteenth century that it began to be appreciated at all widely that geology could be of service to the State. Before 1850, however, a number of Geological Surveys had been established in various parts of the world.

It has often been stated that the Geological Survey of Great Britain, formed in 1835, was the first of all national surveys, or, at least, the first to have had a continuous existence since its inception. In the course of the speeches made in 1935, during the Centenary Celebrations of our Survey, a generous tribute was paid to it by the veteran French geologist, E. de Margerie (Flett, 1937). He referred to it as "the venerable institution which remains as the direct ancestor and prototype of every other Geological Survey now operating anywhere on the surface of the globe". He also mentioned, in passing, a geological map of France prepared by Elie de Beaumont and Dufrénoy, and published at the cost of the state, many years before a formal Survey was organized in France in about the year 1867. The impression is thus left that there was no formal Survey in France before this date.

For reasons to be stated below, it is suggested that de Margerie, in making these statements, perhaps out of politeness to his hosts, did less than justice to his own country. Recently the writer, after examining the origins of state geology in France, concluded that a case could very well be made out that would give to France, rather than to Britain, the honour of having first established a national Geological Survey. Statements made in good faith in serious scientific

[1] Published by permission of the Director of H.M. Geological Survey.

publications may, unless controverted, attain the status of facts simply by constant repetition. For this reason, and because the story of the establishment of a Geological Survey in France as early as 1825 is in itself of considerable interest, it seems desirable that the facts should be placed on record in this country.

The story is fully documented in contemporary French publications (mainly in the *Journal des Mines*, succeeded, in 1816, by the *Annales des Mines*) ; and, in outline, has not passed entirely without notice in Britain. It has been related by Lebour (1876), but he does not make it clear that the survey he describes was organized and financed by the State (nor is his account readily accessible). Sir Archibald Geikie (1905, p. 456) refers to the map of Elie de Beaumont and Dufrénoy as having been begun in 1825 and completed in 1840. He also states that these two geologists belonged to the Mines Department, and that the map was prepared as a national undertaking, but does not enlarge on this aspect of the matter. Topley (1885, pp. 9–10), after noting that the existing French Survey, the *Service de la Carte géologique detaillée de la France*, was established in 1867, gives a short and not entirely accurate account of the earlier Survey by Elie de Beaumont and Dufrénoy, and remarks that, in addition to the map, other official publications appeared before the establishment of the *Service de la Carte géologique*. There are also a number of contemporary references in the early *Proceedings of the Geological Society*, which will be mentioned below.

The most complete account of the circumstances leading up to the formation of this early Survey of France is contained in an unsigned article in the *Annales des Mines* for 1827 (2nd ser., vol. 1, p. 381), entitled " Notice du Plan de faire exécuter une Carte géologique générale de la France ". The history of the execution of the Plan, and of the publication of the resultant map has been related by Brochant de Villiers (1841, pp. iii–xvi), under whose direction the work was carried out. Here, in somewhat condensed form, is the story, based on these two sources, except where otherwise indicated.

As early as 1781 an Inspectorate of Mines was created by Louis XVI, and in 1783 he instituted a School of Mines. Among the subjects to be taught in the latter, all more or less closely related to mining and metallurgy, mineralogy was included. This term, in the broad sense in which it was then used, almost certainly included matters that would now be classed as geological rather than mineralogical. The graduates of the three-year course in this school were the source from which the mines inspectors were to be drawn.

The outbreak of the Revolution in 1789 appears to have completely disorganized, if it did not entirely stop, the activities just mentioned. Towards the close of the Revolution the *Comité de Salut Public* was

apprehensive of the consequences that might result from too long an interruption of studies, and in 1794, almost before the Reign of Terror had ceased in France, they established an *Agence des Mines* under the authority of the *Commission des Armes et Poudres*. In the same year the *Comité* re-established the School of Mines, in which, in addition to mineralogy, geology was taught, under the name "physical geography". In 1794, also, the *Journal des Mines de la République* commenced publication. In the first volume of the *Journal* (1794, p. 8) it was stated that one of the duties it would undertake, conjointly with the *Agence des Mines*, was the collection and publication of material for a mineralogical description of France (see Migneron, 1846, for further details of the foregoing period).

The collection of information relative to the geology of France, and its publication in the *Journal des Mines* continued, apparently until about 1810. Meantime, the title of the *Agence des Mines* had been changed to *Corps des Mines*, and it was now administered jointly with the *Corps des Ponts et Chaussées* (a Public Works Department, in modern phraseology), and the *Ecole des Mines* was a subsidiary of the *Corps des Mines*. In 1816 a Royal statute or order of 5th December was issued relative to the administration of the *Ecole des Mines*. This especially charged the chief administrator of this Institution to collect and assemble all material necessary for the completion of the mineralogical description of France, one of the means to be employed being specified as the making of different maps on which would be traced the different formations and the nature of the soils (*Annales des Mines*, vol. i, 1816, p. 529).

Becquey, to be named one year later as Director-General of the *Corps Royal des Ponts et Chaussées et des Mines*, realized the great importance of this work. It was not, however, until 1822 that circumstances became sufficiently favourable to permit preliminary steps to be taken, with a view to starting it on a systematic basis.

In 1822 the following plan was adopted. It was realized that a map would be necessary to accompany the mineralogical and geological description of France, on which ought to be indicated all information that might be of value at one and the same time to geologists, mining interests, and all other arts dependent for their execution on mineral substances. It was further realized that, for a country the size of France, if all the desired information were to be indicated without confusion, a map on a very large scale would be necessary, which would have to be issued in a large number of separate sheets. This subdivision, it was thought, would have the disadvantage that the map as a whole would not readily be usable in reading general geological reports, and in examining the full extension of the different rock formations which, as well as being of interest to scientists, are

the only means of giving a clear idea of the position of deposits of useful minerals. It was therefore decided to prepare first a general map of medium size, a *Carte générale*, which would be confined within a single sheet, and show only the general geology and, later, detailed maps for each *Département*, or even for certain *Cantons*, to contain all the details. The *Carte générale* was to be the essential base of the mineralogical description of France.

Whilst the importance of utilizing pre-existing information, such as the geological map of France by d'Omalius d'Halloy, published in 1822,[1] and many other Memoirs in the *Journal* and *Annales des Mines* was appreciated, it was also realized that this material did not by any means cover the whole of France, and needed much amplifying.

It was at first thought that the engineers of the *Corps Royal des Mines*, stationed at various points in France, might be entrusted with the execution of the plan ; but it was also clearly recognized that the normal official duties of these officers would interfere with the collection of geological information in the systematic way that was desirable. Such work as they might undertake would be restricted to one or two *Départements*, whereas geological research makes it almost always desirable to follow particular formations for long distances before exact conclusions as to their general characters can be formulated. It was therefore decided not to leave the work entirely to the officers of the *Corps des Mines* but to augment such work as they might do by some more systematic survey (" *voyages pour la Carte géologique* "). Further, the Director-General preferred that these " *voyages* ", having for special object the completion of the *Carte générale*, should be undertaken by *ad hoc* engineers to be engaged solely in the study of geology. The collection of additional details by the engineers of the *Corps des Mines* already stationed in the *Départements* was to be reserved until later, when they could either rectify or complete the general map and prepare the detailed maps of the *Départements*. The *ad hoc* engineers, after covering separate areas in the summer, would return to Paris for the winter to co-ordinate the work carried out during the summer. They would then edit their memoirs and study and classify the suites of specimens sent in to the School of Mines. Above all, they would communicate their observations to and consult with geological specialists. The latter aspect of the work, consultation

[1] The map to which reference is made is the *Essai d'une Carte géologique de la France, des Pays-Bas et de quelques contrées voisines. Dressé par J. J. d'Omalius d'Halloy d'après des materiaux recueillis de concert avec M^r le Baron Coquebert de Montbret*, that accompanies an article entitled *Observations sur un essai de Carte géologique de la France*, etc., by d'Omalius d'Halloy, in the *Annales des Mines*, vol. vii, 1822, p. 353. It is on a scale of approximately 1 : 2,900,000, and, as its title indicates, little more than a sketch or broad generalization of the geological features of France.

with other geologists, especially those familiar with the geology of other countries, was especially emphasized, it being stated that amongst the observational sciences there is none for which intercommunication with other scientists is more necessary.

When the Director-General, Becquey, had decided that this was the method by which the Survey was to be carried out, Brochant de Villiers, Professor of Geology in the School of Mines, was appointed as Director. He was charged with the regulation of the work, the collection and study of all the existing documents, and with all functions normally associated with a Director of Operations and, finally, with inspection in the field. Two young engineers of the *Corps des Mines*, Dufrénoy and Elie de Beaumont, were detailed to carry out the field work necessary for the general map.

The Director-General thought, however, that before commencing operations it would better ensure success if the three engineers were first sent to England to make contact with the scientists who had collaborated in the preparation of the excellent geological map of that country published recently (almost certainly Greenough's map, published in 1820 [1]). He also thought it necessary for them to acquire a sound knowledge of the new discoveries concerning the Secondary formations made in the preceding twenty years (they would, of course, already be familiar with the work of Cuvier and Brongniart on the Tertiary rocks). The expedition, it was thought, would also accustom MM. Elie de Beaumont and Dufrénoy to working in co-operation with Brochant de Villiers and secure that conformity of views so desirable in an undertaking of such magnitude as the preparation of a geological map of France.

The visit, which lasted about six months, took place in 1823. Whilst in England Elie de Beaumont and Dufrénoy received every assistance from the English geologists in carrying out their mission, during which they also visited numerous mines and metallurgical plants.[2] After their return the year 1824 was devoted to editing their notes and classifying the numerous specimens they had collected.

Field work for the geological map commenced in 1825. Elie de Beaumont was allotted the area north and east of a line extending from the coast at Honfleur eastwards to Alençon and Avallon, and

[1] Geikie (1905, p. 456) records that a copy of Greenough's large geological map had been sent to the *Ecole des Mines* in Paris in 1820.

[2] An account of their visit to England was published in 1827, but deals mainly, if not entirely, with their mining and metallurgical studies. The work is entitled *Voyage Métallurgique en Angleterre, ou Recueil de Mémoires sur le Gisement, l'Exploitation et le Traitement des Minérais d'Étain, de Cuivre, de Plomb, de Zinc et de Fer, dans la Grande-Bretagne*. These *Mémoires* had previously been published separately in the *Annales des Mines* between 1824 and 1827.

thence south-eastwards to Châlons-sur-Saône, and southwards down the Saône and Rhône valleys to the Mediterranean ; and Dufrénoy was to work to the west of this line. They were, however, authorized to extend their journeys outside these limits where necessary to ensure the accuracy of their lines, and even, for this purpose, to enter neighbouring countries. In 1826, to ac elerate the work, the Director-General appointed M. Billy and M. Feneon to assist Dufrénoy and Elie de Beaumont, respectively. Records of progress were published at intervals in the *Annales des Mines*. This seems to have been virtually if not actually a government publication ; and, so far as its geological content is concerned, may be compared with the *Summary of Progress* of our own Geological Survey.

The field work for the *Carte générale* was completed by 1835, and in that year an advance coloured copy of the map was exhibited before the Academy of Sciences in Paris (Brochant de Villiers, 1841, p. xiv). Publication was not achieved until 1841, the delay resulting from the necessity of first preparing a specially engraved topographical map as a base for the geology. The *Carte générale* was issued in six separate sheets, on a scale of 1 : 500,000 (8 miles to 1 inch). It bears the following title :—

> Carte géologique de la France. Executée sous la direction de Mr Brochant de Villiers, Inspecteur Général des Mines, par MM. Dufrénoy et Elie de Beaumont, Ingénieurs des Mines. Commencée sous l'Administration de Mr Becquey, Director Général des Ponts et Chaussées et des Mines, terminée en 1840. Mr Le Comte Jaubert Ministre des Travaux Publics, Mr Legrand Sous-Secrétaire d'Etat au Même Département.

The map is a splendidly produced publication, attractive in appearance, and remarkably detailed for its time. On it are indicated, in colour, no less than thirty-seven different rock types and formations with, in addition, a considerable number of letters and signs to indicate deposits of useful minerals. There are twenty-four subdivisions of the sediments and, as an indication of the fact that the geologists responsible for the map kept abreast of the times, it may be mentioned that Cambrian, Silurian, and Devonian (" Vieux Grès rouge des Anglais ") are differentiated on the map. Thirteen varieties of crystalline schists and igneous rocks are shown. By any standard the map must be accounted a remarkable achievement, but more especially if allowance is made for the period in which it was constructed. On the question of its accuracy we may quote the opinion of de Margerie (p. 232), who refers to it as the first geological map of France " following truly scientific principles ", and states that with the exception of the " great mountain chains in the south and south-east, the complexity of whose structure was then unsuspected, the geological

picture traced by these two masters remains, after seventy-five years, surprisingly exact ".

Between 1830 and 1838 the authors of the map issued, in four volumes, a publication entitled *Mémoirs pour servir à une Description géologique de la France*, a reprint of their progress reports already printed in the *Annales des Mines*. After the map was completed they commenced the publication of a series of elaborate official Memoirs entitled *Explication de la Carte géologique de la France*, embodying in detail their considered views. The first appeared in 1841, a quarto volume of 825 pages, in which was included a coloured replica of the large map, on a scale of 1 : 2,000,000, entitled *Tableau d'assemblage des six feuilles de la Carte géologique de la France*. A second volume of the *Explication* appeared in 1848, and a third in 1873.

The above volumes were not actually the first official Memoirs to be published, for there was issued in 1836 a work by H. Fournel, *Études des Gîtes Houillers et Metallifères du Bocage Vendéen*, evidently the first of a series entitled *Études de Gîtes Minéraux publiée par les Soins de l'Administration des Mines*. This may be compared with the *Special Reports on the Mineral Resources of Great Britain* series of our own Survey, though I have not been able to discover that any later volumes were published.

This, in brief, is the story of the first Geological Survey of France. It resulted from a systematic plan, carefully thought out in advance by officials of the State, and carried out at the expense of the French government. The plan might well have been put in operation at an earlier date but for the disturbed political conditions in France in the first decade or two of the century. Brochant de Villiers (1841, p. vi) records that he put a project for a geological map before the Director-General of the *Corps des Mines* in 1811 but that it was not then acceptable to the Government. Once agreed upon, however, in 1822, the plan described above was carried through methodically and with expedition, and its first objective, the *Carte générale*, was completed in a comparatively short time.

Space does not permit a discussion as to how far the second aim, the production of detailed maps of the Departements, was prosecuted, but it is clear from information published in the *Annales des Mines* that active work in preparation of these maps continued on an official basis after the publication of the *Carte générale*, and de Launay (p. 77, footnote) records that between 1828 and 1868 forty-four such maps were published, though not all appear to have been official in origin.

In 1868 a new Geological Survey, the *Service de la Carte géologique detaillée de la France*, was inaugurated by an Imperial decree of the 1st October. A link with its forerunner is provided by the fact that Elie de Beaumont was appointed its Director, and, in fact, he seems

to have been largely instrumental in re-establishing the Survey again on a formal basis. As the title of the new Survey indicates, it was to prepare maps on a more detailed scale than hitherto, and the scale selected was 1 : 80,000 (approximately $\frac{3}{4}$ in. to 1 mile). Henceforward, the Survey appears to have continued on methods roughly comparable with our own, at least in the matter of publications. The whole country was divided into a grid and the maps published on sheets comparable in size to the 1 in. to the mile sheets of our own Survey. Sheet explanations and vertical and horizontal sections were also issued.

The importance of the *Carte générale* was soon recognized in England, a copy having been presented to the Geological Society in December, 1841. Indeed, from the time of its completion in 1835, and whilst still in the hands of the engravers, it seems to have been freely accessible to visiting geologists, and Murchison (1842) records seeing it in Paris on more than one occasion. In 1843 the work of the two geologists who had carried out the Survey, Dufrénoy and Elie de Beaumont, was recognized by the joint award of the Geological Society's highest honour, the Wollaston Medal.

Turning again to the question of priority in the establishment of a national Geological Survey, some remarks made by Professor Buckland (1840 and 1841) in successive Anniversary Addresses to the Geological Society are apposite. In commenting on the geological maps of Devon and Cornwall just produced by De la Beche, the first fruits of the newly established British Geological Survey, he characterized them as " documents to which we can at length with pride appeal, in reply to the reproach that has so long, with too much truth, been cast upon us, that England alone, of all the civilized nations, has abandoned to gratuitous individual exertions, and the liberality of amateurs in science, the great work of exploring and delineating the mineral structure of the country " ; and again, in 1841, " . . . the commission not long since given to Mr. De la Beche, to colour geologically the Ordnance Map of the West of England and the district of the Coal formation of South Wales, afford almost the first example of the tardy recognition by the British Government of the vast public importance of the practice which has for nearly twenty years been acted on in France and the United States, in appointing a commission of eminently qualified scientific men to survey and report on the Mineral and Geological productions of the country and express the same by colouring on the most perfect maps."

Looked at now, in historical perspective, the question of priority is not, perhaps, of great moment. Yet it is of interest to note that France was much earlier in the field than has generally been realized, not only in recognizing the usefulness of a Geological Survey to the State, but in putting the idea into execution.

Addendum

Since the above was written the author's wife, whilst examining a collection of papers and correspondence left behind by Robert Jameson, Professor of Natural History in the University of Edinburgh from 1804 to 1854, and now in the University Library in Edinburgh, came across a letter addressed to Jameson from Paris on 22nd February, 1829, that mentions the Geological Map of France as then being in course of preparation, and throws an interesting sidelight on the activities of the *Ecole des Mines* at the time. The letter was written by one William Bald, apparently a Scotsman, but not, as far as can be ascertained, a relative of Robert Bald, a mining engineer well known in Scotland at that time. All that appears from William Bald's letter, apart from the quotation below, is that he was actively engaged in the preparation of solid geological models, for which he received payment.

The relevant portion of the letter, quoted by kind permission of Dr. L. W. Sharp, Librarian to the University, Edinburgh, is as follows :—

" I had the pleasure the other day of examining in the l'Ecole Royal des mines the Geòlogical map which is now making of France, this work was commenced in 1825 under the direction of M. Brochant de Villers member of the Institute ; M. Dufrenoy assisted by M. de Billy for one half of France south west, and your friend who enquired very kindly for you M. Elie de Beaumont assisted by M. Fénéon for the other half of France.—all the specimens are beautifully arranging in the l'Ecole Royal des mines of each district ; there are seven rooms upon the second story 198 feet long by 27 feet broad ; and four rooms below more than 120 feet long.—The public lectures commence on the 15th Novr. and end on the 15th April every day except Sunday by M. Gueneyveau ; M. Baillet, M. Brochant and M. Berthier.—It is truly delightful to see a government protecting and upholding institutions which tend so much to the progress of civilization, industry and national wealth."

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CORRESPONDENCE

FLOOR OF THE ENGLISH CHANNEL

SIR,—During the last three years a programme of research has been carried out to obtain further data regarding the solid rocks forming the floor of the English Channel. At the present time three areas have been investigated and further work is being planned. The research is being carried out in conjunction with the Department of Geophysics of Cambridge University, which has been responsible for the construction of the necessary apparatus under the direction of Mr. M. N. Hill. A corer modified from that used in the United States under the name of the Stetson corer has been used. The research vessel *Sabella*, of the Marine Biological Association at Plymouth, has been used for this work and I should like to express my thanks to the Director for the generous aid he has given by allowing us the use of the ship, and to the Captain and crew for the way they have manipulated the apparatus. The work is still in progress, but it is felt that a preliminary note on the main facts disclosed to date would be of interest.

Area 1.—Samples were taken along a line south of Plymouth to 18 miles south of the Eddystone. New Red Sandstone deposits (red sands and rubbly marls) were proved from 50° 15·3′ N.–4° 9·9′ W. (8 m. south of Plymouth) to 50° 6·7′ N.–4° 15·5′ W. (5½ m. south of the Eddystone), showing that the outcrops of the Eddystone–Rutts–Start Point are peaks of the Pre-Cambrian ridge jutting through an infilling of New Red Sandstone deposits. At 50° 0·8′ N–4° 16·6′ W. (12½ m. south of the Eddystone) a sample of chocolate-brown marl of the appearance of Keuper Marl was obtained and at 49° 55·9′ N.–4° 15·6′ W. (about 18 m. south of the Eddystone) a sample of hard white chalk, black flint, and a pebble of glauconitic chalk was obtained.

Area 2.—Mid-Channel between the Isle of Wight and Cherbourg. The majority of the cores obtained are of Recent muddy sands or fine white clayey sands and sandy clays which have as yet not been identified with certainty, but the majority of these samples yield fragments of carbonaceous material on washing. It is thought that these are probably Wealden, since they occur between proved Upper Jurassic and Chalk outcrops. Of sites about which definite statements can be made, the following are the most important :—

(*a*) Chalk at 50° 14½′ N.–1° 24′ W.
50° 26′ N.–1° 22′ W.
50° 09′ N.–1° 36½′ W.
50° 20′ N.–1° 57′ W.

(*b*) Shales with ostracods, Purbeck or Wealden
50° 14′ N.–1° 11′ W.

Purbeckian–Portlandian. The dredge brought up lithographic limestone of "shrimp bed" type, cherty fresh-water limestone with Chara and shale with ostracods
50° 18′ N.–1° 25½′ W.

Upper Kimmeridge Clay with ammonite fragments
50° 17½′ N.–1° 25′ W.

(these latter two have been checked by Dr. W. J. Arkell).

Dark shale with Lingula fragment	50° 15½′ N.–1° 21′ W.
Dark jet-like shale	50° 14½′ N.–1° 15′ W.
Shaley clay with shell fragments	50° 16′ N.–1° 22′ W.

These three are also probably Kimmeridge Clay.

The fine white clay sands and clays noted above occur north and north-east of the sites (*b*) and south of the main chalk areas noted on the Admiralty charts and confirmed by the corer. It should be noted that in all the good cores obtained the dip of the strata was horizontal or of a value of only a few degrees.

Area 3.—A series of samples were obtained on a line between 40° 34½′ N.–3° 05′ W. to 49° 47′ N.–3° 19′ W., that is from a point about 20 miles W.N.W. of Guernsey to half-way across the Channel on a course to Plymouth.

Chalk was proved at a number of points. At 49° 47′ N.–3° 06′ W. in 41 fathoms a core of brick-red marl with a few tea-green streaks was obtained. The age of this deposit has not yet been determined but its appearance is similar to some of the New Red Sandstone deposits in the Eddystone neighbourhood.

W. B. R. KING.

SEDGWICK MUSEUM,
CAMBRIDGE.
20th August, 1950.

DIORITES AND APPINITES

SIR,—I was interested in the article entitled " The diorites and associated rocks of the Glen Tilt Complex, Perthshire—II. Diorites and appinites ", by W. A. Deer, in your issue for May–June of this year. In Southern Rhodesia typical appinites are fairly common and their field relations support the author's conclusion that they are essentially hybrids. They are found in areas of migmatites and composite gneisses in the marginal zones of many of our " schist belts " and also as lenticular masses enveloped in the granitic rocks of the batholiths, often some miles from the nearest schist belt. There seems every indication that they are the result of a " soaking " of basic members of the Basement Complex (epidiorites and hornblende-schists) by granitic material, and the common occurrence of diopside in the finer-grained portions between the hornblende phenocrysts (which themselves sometimes have pyroxenic cores) suggests plutonic metamorphism at very great depths. Oligoclase, microcline, and quartz are usually associated with the pyroxene in the groundmass, while apatite is normally an abundant accessory mineral. At one locality a variety of striking appearance shows ovoids of sodic plagioclase up to an inch or more across, frequently with a kernel of black hornblende. As in the case of the Glen Tilt occurrences, the rocks are heterogeneous and there are no sharp contacts with adjacent granite or hornblendic gneisses. They provide some of the most handsome rock types in this country.

R. TYNDALE-BISCOE.

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SOUTHERN RHODESIA.
10th July, 1950.

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A vacancy exists for an Engineer-Geologist in the Public Works Department, Kenya. The appointment is on contract for four years. The salary scale is £690–£1,320 a year (promotion bar at £1,140), and the point of entry into the scale would be determined according to experience and war service. The rate of income tax is considerably lower than in the United Kingdom. Free passages are provided for the officer and his wife and children on appointment and on termination of contract, up to a maximum of three adult passages in all. Eighteen days' local leave is granted per annum, and vacation leave is granted at the rate of four and half days for each completed month of resident service. Rent for government quarters amounts to 10 per cent of salary if furnished and 7½ per cent if unfurnished. Where the rent paid by officers occupying private quarters exceeds these amounts a suitable allowance is made. There is an acute housing shortage at present and a single candidate would, therefore, be preferred. Candidates should preferably be under 30, but a small allowance may be made for war service. They must hold a University degree with Geology as a major subject. Preference will be given to those who are Fellows of the Geological Society and/or who are qualified mining engineers. They must have good all-round experience, and must be capable of carrying out geo-physical surveys and investigations for the location of sub-surface water supplies by boring shallow wells, etc., and of undertaking the investigation, survey, and design of very small works for the conservation and development of surface supplies, particularly by means of earthdams and excavation tanks. Candidates should write at once, giving brief particulars of age, qualifications, and experience, to the Director of Recruitment (Colonial Service), Colonial Office, Sanctuary Buildings, Great Smith Street, London, S.W. 1, quoting reference number 27079/18/50.

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